A User's Guide to EnergyPLAN

David Connolly
University of Limerick

david.connolly@ul.ie
www.cpi.ul.ie

13 April 2010
Version 3

I would like to thank Prof. Henrik Lund and Assistant Prof. Brian Vad Mathiesen for all their help during my time at Aalborg University.

Print Double-Sided

Table of Contents

Section	Title	Page
Table of Contents		**1**
1	**Introduction**	**2**
2	**Why EnergyPLAN?**	**3**
3	**Collecting the Required Data**	**4**
3.1	Data for a Reference Model with a Technical Optimisation	5
3.1.1	Input Tab	6
3.2	Data for Future-Alternatives with a Technical Optimisation	21
3.2.1	Photovoltaic	21
3.2.2	Tidal	21
3.2.3	Wave Power	22
3.2.4	Future Additions	24
3.3	Data for Costs	25
3.3.1	Fuel Tab	25
3.3.2	Operation Tab	27
3.3.3	Investment Tab	28
3.3.4	Additional Tab	30
4	**Areas of Difficulty**	**31**
4.1	Thermal Energy System	31
4.2	District Heating Groups	32
4.3	Technical Optimisation vs. Market Optimisation	32
4.3.1	Business-economic vs. Socio-economic calculations	33
4.4	Optimisation criteria for an Energy-System	34
4.5	External Electricity Market Price	34
4.6	Operation Strategy for Electricity Storage	34
4.6.1	Storage capacity for the double penstock-system strategy	36
4.7	Description of 'stab.-load' from EnergyPLAN results window	38
5	**Verifying Reference Model Data**	**41**
6	**Common Error Screens**	**42**
6.1	Wrong Number of Data Points	42
6.2	Distribution File Location	43
6.3	Warnings	44
7	**Conclusions**	**46**
8	**Appendix**	**47**
8.1	Ireland's Energy-Balance 2007	47

9 References..... 48

1 Introduction

This is a brief description of my experience when I learned how to use the energy tool EnergyPLAN [1]. It is a short description of why I chose EnergyPLAN for my particular study, followed by a brief account of the sources I used to gather the data for the model.

When I was carrying out my work using EnergyPLAN, I did not know where to begin looking for a lot of the data I needed. As a result, the primary aim of this document is to share with others where or how I found the required data for my model. I hope that this brief overview of my experience will enable the reader to use EnergyPLAN quicker and more effectively. Finally, I welcome any contributions that could be made to improve the content of this document, such as new sources of data or suggestions for new content. If you have any further questions or contributions regarding any of the material in this document, please don't hesitate to contact me at david.connolly@ul.ie.

2 Why EnergyPLAN?

Before choosing the energy tool I would use, I had to decide what exactly I wanted to do. After some deliberation, I decided that the model for my investigation must be able

"To identify how Ireland could integrate the most renewable-energy into its energy-system".

This statement, although broad at first, did limit my selection of energy tool quite substantially. An overview of all the energy tools I considered, as well as many others can be found in [2], and therefore these will not be discussed in detail here. Instead the reasons that I chose EnergyPLAN are discussed.

There were a number of reasons that I chose EnergyPLAN for my study:

1. It was simple to use and hence the training period would be short. Also in relation to this point, there is online training available from the EnergyPLAN website so it is easy to experience a typical application of the software [1].
2. The EnergyPLAN software is free to download [1].
3. EnergyPLAN considers the three primary sectors of any national energy-system: electricity, heat and transport.
4. EnergyPLAN was used to simulate a 100% renewable energy-system for Denmark [3].
5. Prof. Henrik Lund is actively publishing his results using EnergyPLAN within academic journals. A number of energy-model developers publish their results in private reports for those who fund their investigations. However, in order to obtain my PhD qualification I needed to publish my work in academic journals. Therefore, it was fortunate and important that EnergyPLAN was being used for this purpose.
6. The quality of journal papers being produced using EnergyPLAN was a key attraction. Below are a few examples of the titles I recorded before contacting Prof. Henrik Lund about EnergyPLAN:
    a. Energy system analysis of 100% renewable energy systems – The case of Denmark in years 2030 and 2050 [4]
    b. The effectiveness of storage and relocation options in renewable energy systems [5]
    c. Large-scale integration of optimal combinations of PV, wind and wave power into electricity supply [6]
    d. Large-scale integration of wind power into different energy systems [7]

    After reading these journal papers and observing the contribution that the results made to the Danish energy-system, I felt that I could supply a similar insight into the Irish energy-system using EnergyPLAN.
7. Finally and possibly the most important reason for using EnergyPLAN, was Prof. Henrik Lund's supportive attitude when I approached him about using EnergyPLAN. I was invited to Aalborg University to learn about EnergyPLAN and complete my first model. My progress has been accelerated beyond expectation due to the support and guidance from both Prof. Henrik Lund and Associate Prof. Brian Vad Mathiesen during my time at Aalborg University. This is an essential aid when embarking on research, especially when deadlines need to be met.

3 Collecting the Required Data

As mentioned above, once I decided that EnergyPLAN was the most suitable energy tool for my particular study, I moved to Aalborg University for a short period to learn how to use the software correctly. During my time there, I completed a reference model of the existing Irish energy-system. However, I felt that a lot of my questions could have been answered if I simply knew where to begin looking for the data required. Therefore, I decided to complete this document which simply discusses where I found the information I needed to complete my reference model of the Irish energy-system. I hope that this will enable future EnergyPLAN users to collect their data more effectively.

Important: There are important points below that need to be considered when reading the following chapters:

1. I have discussed a number of inputs in great detail and others only briefly. This reflects the effort required and the assumptions made in order to get the data and **not** the importance of the data.
2. When you download the EnergyPLAN model, a number of distributions are included with it. In a lot of studies these distributions will suffice as the results from the EnergyPLAN model may not be greatly improved by a more accurate distribution. Therefore, it is worth analysing the effects of various distributions on your results before allocating large periods of time to creating distributions.

This chapter is divided into **three** primary sections:

1. Data for a Reference Model with a Technical Optimisation
2. Data for Future-Alternatives with a Technical Optimisation
3. Data for Costs

The order is used as this is a typical modelling sequence that is recommended when simulating an energy-system. Firstly, a reference model must be created to ensure that EnergyPLAN can simulate the energy-system correctly, before introducing alternatives. The reference model does not require economic inputs, as it is usually only the technical performance that can be compared (i.e. cost data is usually not in the public domain). After creating the reference model using the technical inputs, then the fuel, investment, and O&M costs can be added to carry out a socio-economic analysis of the energy-system. Therefore, alternatives can now be created and compared in relation to their technical performance and annual operating costs. Finally, the external electricity market costs can be added so a market optimisation can be completed in EnergyPLAN: this enables you to identify the optimum performance of the energy-system from an business-economic perspective, rather than a technical perspective. However, typically the aim when creating future alternatives is to identify how the optimum business-economic scenario, can be altered to represent the optimum socio-economic scenario (i.e. by adjusting taxes) as this is the most beneficial for society.

Finally, before discussing the data that was collected, it is important to be aware of the type of data that EnergyPLAN typical requires. Usually, the EnergyPLAN model requires two primary parameters:

1. The total annual production/demand
2. The hourly distribution of the total annual production/demand
    a. There must be 8784 data points, one for each hour
    b. The data points are usually between 0 and 1, representing 0-100% of production/demand as shown in Figure 1[1]. However, if a distribution is entered with values greater than 1, the program will index the distribution: This is done by dividing each entry in the distribution by the maximum value in the distribution. This means that historical hourly-data can be used in EnergyPLAN for a distribution. An example, displaying how an index is created, and also how an index is used is shown in Table 1.
    c. The distribution is inputted as a text file

[1] This does not apply to the price distributions. For the price distribution, the actual values provided in the distribution are used.

The distribution is simply adjusted to reflect the total annual production/demand. For example, in Figure 2, the distributions for three separate demands are shown. In Figure 2 the three distributions show how the distribution in Figure 1 is manipulated to model the total demand.

Table 1
How a distribution is indexed and subsequently used in EnergyPLAN (Note: 8784 hours in total are required).

Time (h)	Output from a 100 MW Wind Farm (MW)	Index Data		Using Indexed Data to Simulate a 400 MW Wind Farm	
		Fraction	Decimal		
1	20	20/100	0.2	0.2*400	80
2	30	30/100	0.3	0.3*400	120
3	60	60/100	0.6	0.6*400	240
4	100	100/100	1.0	1.0*400	400
5	80	80/100	0.8	0.8*400	320
6	40	40/100	0.4	0.4*400	160

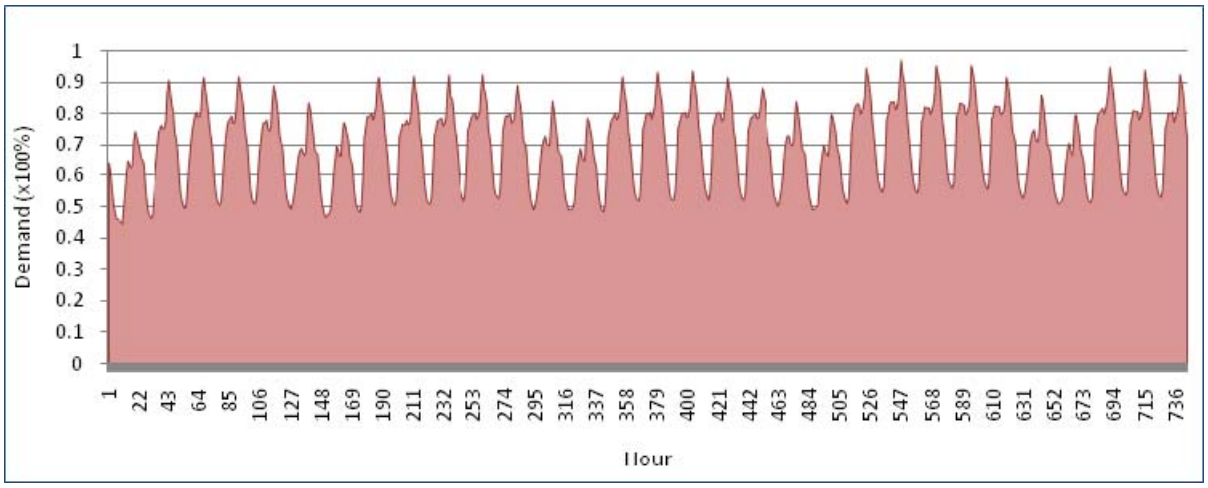


Figure 1: Distribution of Irish Electricity-Demand for January 2007.

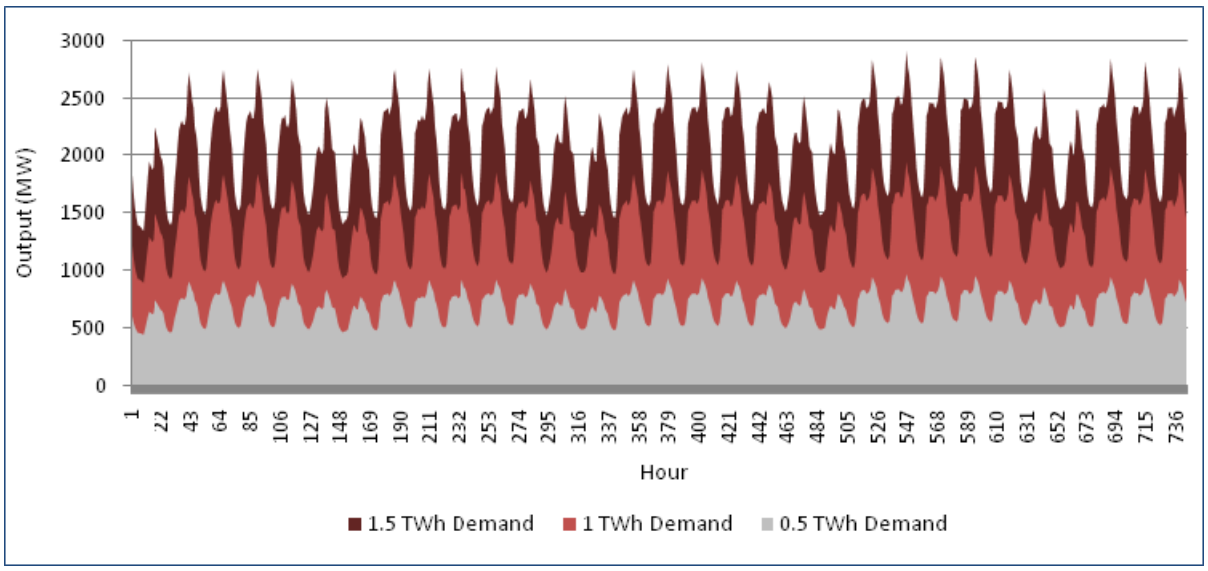


Figure 2: Distribution modified by the total demand required.

3.1 Data for a Reference Model with a Technical Optimisation

EnergyPLAN simulates a single year in hourly time-steps. To create an initial model, I picked the year 2007 as it was the most recent when I started gathering my data.

To explain where I got my data, I will discuss each tab within the EnergyPLAN model separately. The 'Frontpage' tab illustrates a flow diagram of the EnergyPLAN model, indicating how all the various components of the energy-system interact with one another. The 'Input' tab is used to describe the parameters of the energy-system in question. The 'Cost' tab is used to input the costs associated with the energy-system being investigated and the 'Output' tab is used to analyse the results of your investigation. Finally, the 'Settings' tab enables the user to change the data-units in the program.

Below I will discuss in detail where I got the information for the 'Input' tab and the 'Cost' tab, as these account for the majority of data required.

3.1.1 Input Tab

Below is a brief description of the data I used under the 'Input' tab in my model. It is worth noting that the data required for EnergyPLAN is usually generic data that can be obtained in most OECD countries. Therefore, if I was able to obtain the data for the Irish energy-system, it is likely to be available in other countries also. Also note that each sub-heading in this section represents data required for a different tab in EnergyPLAN.

The first piece of information that you should try to source is the 'Energy Balance' for your country or region. The Irish Energy Balance was completed by the Irish energy agency called Sustainable Energy Ireland (SEI) [8]. The Energy Balance indicates the energy consumed within each sector of the energy-system as displayed Figure 3 and Appendix A. The International Energy Agency (IEA) completed two reports on energy balances in 2008: one with the Energy Balances for each of the OECD countries [9] and one with the Energy Balances for a number of non-OECD countries [10]. These documents must be purchased so I have not obtained a copy. However, this is one possible source for an energy balance of your energy-system.

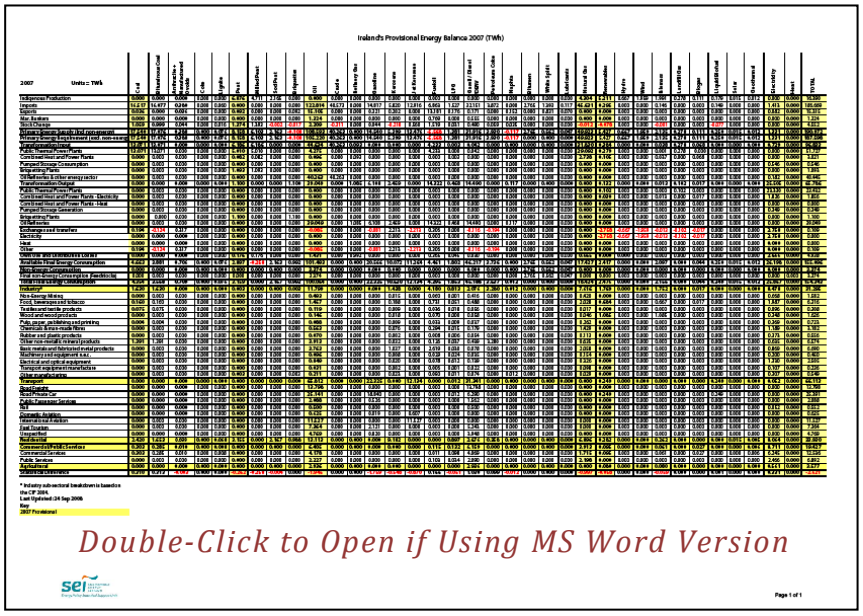


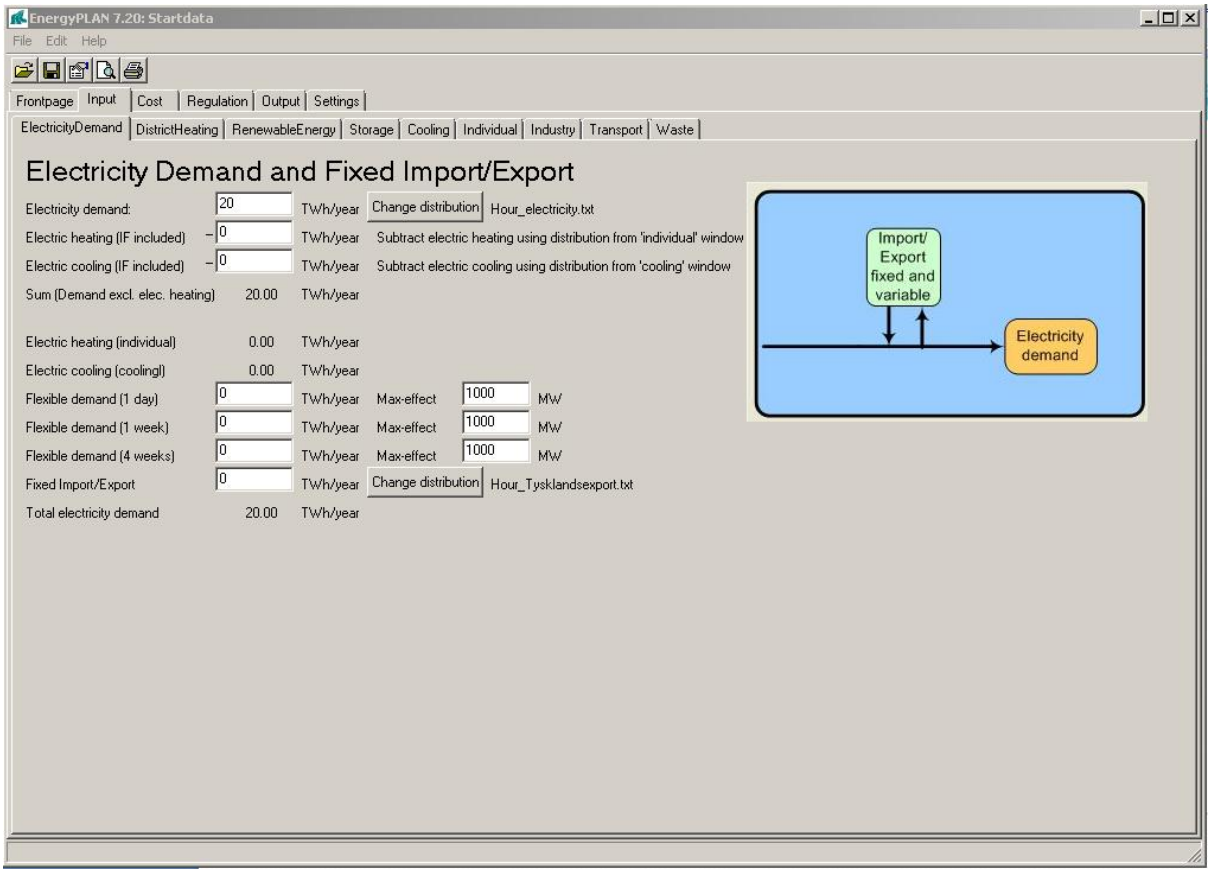
Figure 3: Irish Energy Balance for 2007.

The Energy Balance document proved to be the most useful source of information for my investigation. However, it is important to check the accuracy of the data in this document, as the figures can sometimes be based on estimates.

Secondly, meteorological data also proved very important when predicting renewable-energy production. Meteorological data can usually be obtained from a national meteorological association. However, another option is to use a program called 'Meteonorm' [11]. This program has gathered data from a number of meteorological stations around the world, which can be accessed using a very intuitive user interface. However, the program is not free so you will need to decide how important meteorological data will be before

purchasing it[2]. It is also important, that even if you use this program, that you compare the data in the program to actual measurements to ensure that the program is providing accurate data.

3.1.1.1 Electricity Demand


EnergyPLAN 7.20: Startdata
File Edit Help
Frontpage Input Cost Regulation Output Settings
ElectricityDemand DistrictHeating RenewableEnergy Storage Cooling Individual Industry Transport Waste
Electricity Demand and Fixed Import/Export
Electricity demand: 20 TWh/year Change distribution Hour_electricity.txt
Electric heating (IF included) 0 TWh/year Subtract electric heating using distribution from 'individual' window
Electric cooling (IF included) 0 TWh/year Subtract electric cooling using distribution from 'cooling' window
Sum (Demand excl. elec. heating) 20.00 TWh/year
Electric heating (individual) 0.00 TWh/year
Electric cooling (cooling!) 0.00 TWh/year
Flexible demand (1 day) 0 TWh/year Max-effect 1000 MW
Flexible demand (1 week) 0 TWh/year Max-effect 1000 MW
Flexible demand (4 weeks) 0 TWh/year Max-effect 1000 MW
Fixed Import/Export 0 TWh/year Change distribution Hour_Tysklandsexport.txt
Total electricity demand 20.00 TWh/year
Import/ Export fixed and variable
Electricity demand

Total electricity demand was obtained from the Irish transmission system operator (TSO), EirGrid [8], and the Energy Balance document. Imported and Exported electricity was also obtained from the TSO in Ireland.

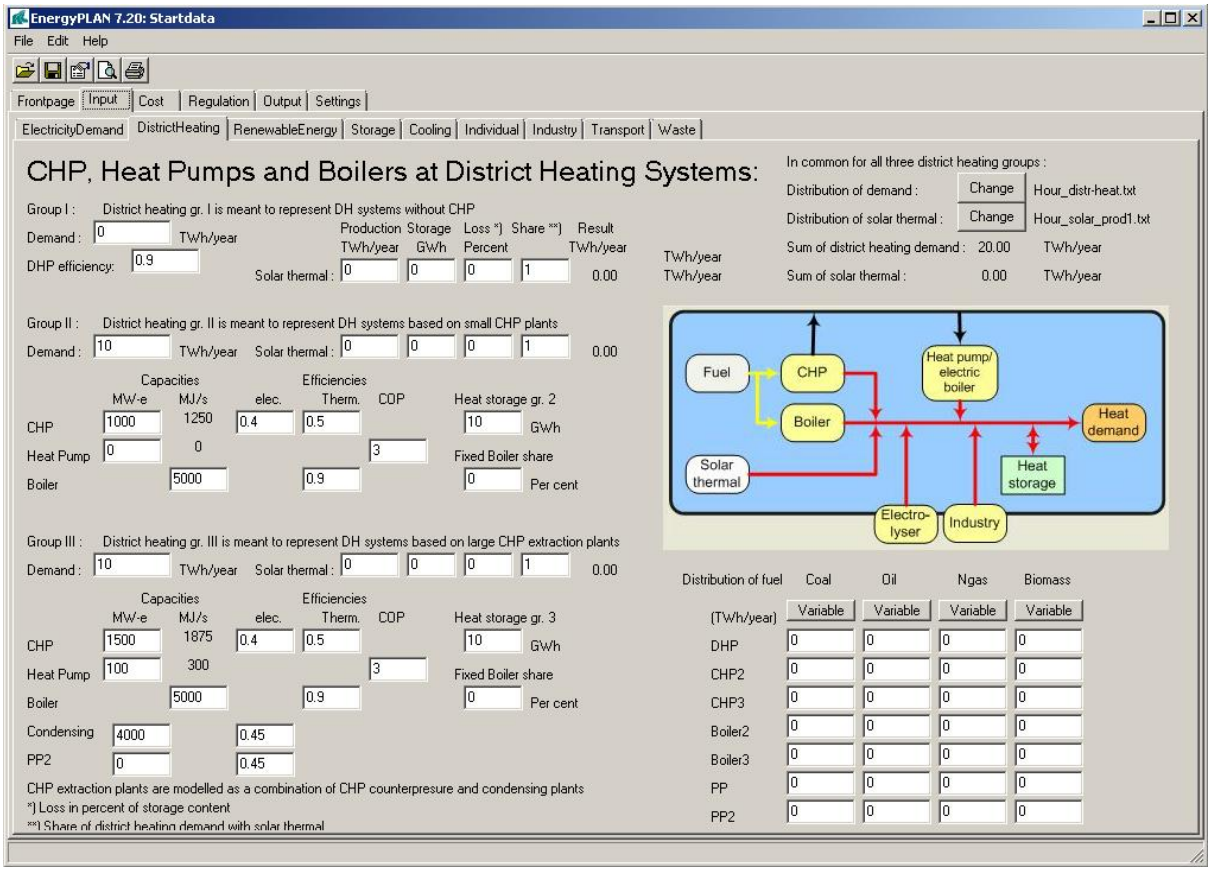
Twenty-four European countries are involved in the 'Union for the Co-Ordination of Transmission of Electricity' (UCTE), which provides a lot of detailed data about the production and consumption of electricity. A list of the countries in the UCTE is available from [12], and the data can be obtained from [13]. The data includes the following:

- Statistics
- Production Data
- Consumption Data
- Exchange Data
- Miscellaneous Data
- Country Data Packages

Therefore, this is a useful source of information if you're modelling a European region.

[2] Data from meteorological stations may or may not be free so enquire

3.1.1.2 District Heating


EnergyPLAN 7.20: Startdata
File Edit Help
Frontpage Input Cost Regulation Output Settings
ElectricityDemand DistrictHeating RenewableEnergy Storage Cooling Individual Industry Transport Waste
CHP, Heat Pumps and Boilers at District Heating Systems:
In common for all three district heating groups :
Distribution of demand : Change Hour_distr-heat.txt
Distribution of solar thermal : Change Hour_solar_prod1.txt
Sum of district heating demand : 20.00 TWh/year
Sum of solar thermal : 0.00 TWh/year
Group I : District heating gr. I is meant to represent DH systems without CHP
Demand : 0 TWh/year
DHP efficiency: 0.9
Production Storage Loss *) Share **) Result
TWh/year GWh Percent TWh/year
Solar thermal : 0 0 0 1 0.00
Group II : District heating gr. II is meant to represent DH systems based on small CHP plants
Demand : 10 TWh/year Solar thermal : 0 0 0 1 0.00
Capacities Efficiencies
MW-e MJ/s elec. Therm. COP Heat storage gr. 2
CHP 1000 1250 0.4 0.5 10 GWh
Heat Pump 0 0 3 Fixed Boiler share
Boiler 5000 0.9 0 Per cent
Fuel
CHP
Boiler
Heat pump/ electric boiler
Heat demand
Solar thermal
Heat storage
Electro-lyser
Industry
Group III : District heating gr. III is meant to represent DH systems based on large CHP extraction plants
Demand : 10 TWh/year Solar thermal : 0 0 0 1 0.00
Capacities Efficiencies
MW-e MJ/s elec. Therm. COP Heat storage gr. 3
CHP 1500 1875 0.4 0.5 10 GWh
Heat Pump 100 300 3 Fixed Boiler share
Boiler 5000 0.9 0 Per cent
Condensing 4000 0.45
PP2 0 0.45
CHP extraction plants are modelled as a combination of CHP counterpresure and condensing plants
*) Loss in percent of storage content
**) Share of district heating demand with solar thermal
Distribution of fuel Coal Oil Ngas Biomass
(TWh/year) Variable Variable Variable Variable
DHP 0 0 0 0
CHP2 0 0 0 0
CHP3 0 0 0 0
Boiler2 0 0 0 0
Boiler3 0 0 0 0
PP 0 0 0 0
PP2 0 0 0 0

For my initial energy model I did not have to include any district heating or CHP as there are currently no large-scale installations in Ireland. However, for the condensing power-plant data, I got a list of the power plants currently in operation in Ireland from the TSO [8]. Using the energy balance document I could calculate the efficiency of all the condensing plant, η_{COND}, using the total fuel input, F_{IN} (Wh), and total electricity generated, $Elec_{TOT}$ (Wh),

$$\eta_{COND} = \frac{Elec_{TOT}}{F_{IN}} \quad (1)$$

It was difficult to obtain the efficiencies of the individual condensing plant as it was "commercially sensitive information". However, I obtained a breakdown of fuel inputted into the Irish condensing plants, see Figure 4, once again from the Irish energy agency SEI, and used this to calculate the efficiencies for the condensing plant of different fuel-type (using formula 1). For the reference model you will not need to know this: instead all you need to find out is the total fuel consumed by all the power plants, and the total electricity generated by all the power plants (then you can calculate the condensing efficiency). However, the efficiency of the power plants under each fuel type will be necessary when simulating future alternatives: for example, if you wanted to simulate coal power plants being replaced by natural gas power plants as illustrated in Table 2.

Table 2
How individual power plant efficiencies alter the overall "Condensing" power-plant efficiency.

	Coal PP (MW)	Natural Gas PP (MW)	Coal PP Efficiency	Natural Gas PP Efficiency	Total Capacity (MW)	Overall Efficiency
Reference	1000	2000	0.4	0.5	3000	0.466
Alternative 1	500	2500	0.4	0.5	3000	0.484
Alternative 2	0	3000	0.4	0.5	3000	0.500

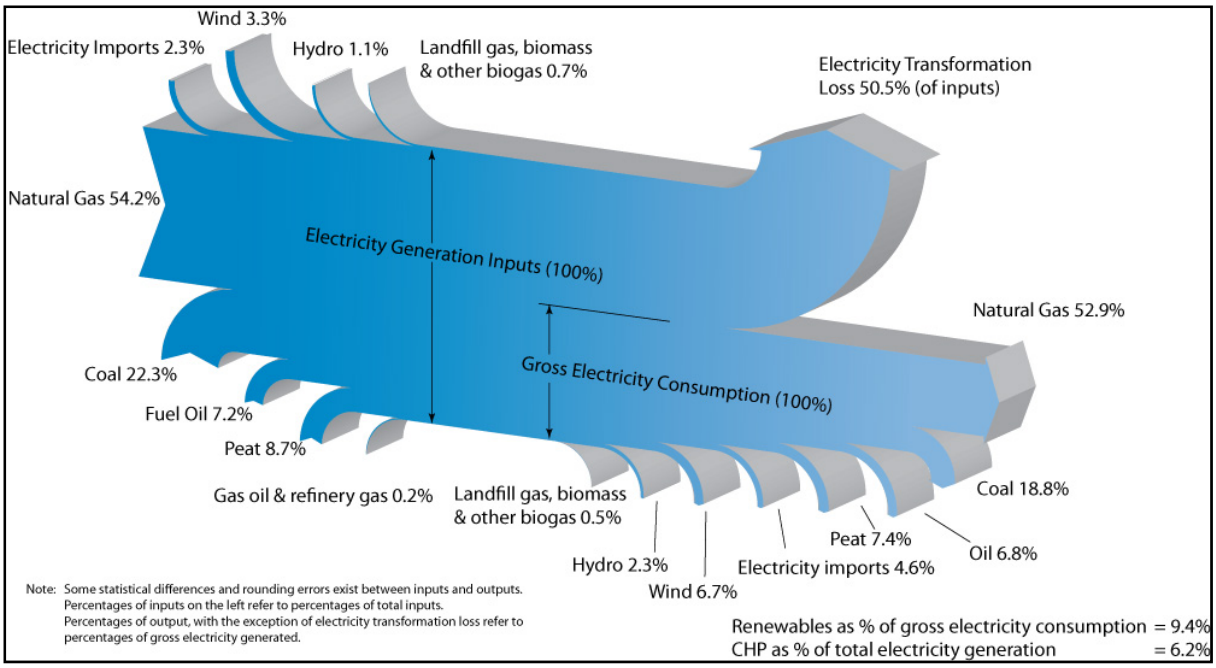
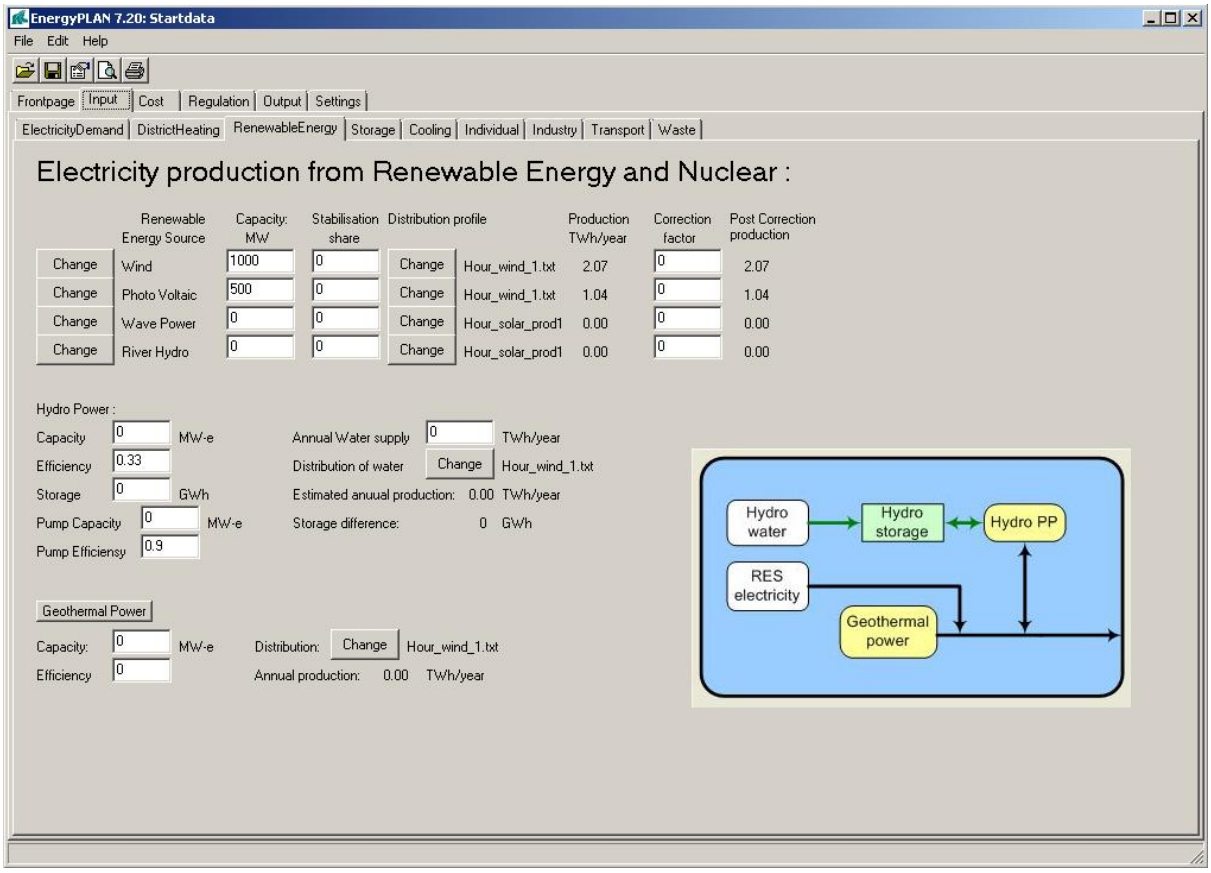

Wind 3.3%
Electricity Imports 2.3%
Hydro 1.1%
Landfill gas, biomass & other biogas 0.7%
Electricity Transformation Loss 50.5% (of inputs)
Natural Gas 54.2%
Electricity Generation Inputs (100%)
Natural Gas 52.9%
Coal 22.3%
Gross Electricity Consumption (100%)
Fuel Oil 7.2%
Peat 8.7%
Gas oil & refinery gas 0.2%
Landfill gas, biomass & other biogas 0.5%
Coal 18.8%
Peat 7.4%
Oil 6.8%
Hydro 2.3%
Electricity imports 4.6%
Wind 6.7%
Note: Some statistical differences and rounding errors exist between inputs and outputs.
Percentages of inputs on the left refer to percentages of total inputs.
Percentages of output, with the exception of electricity transformation loss refer to percentages of gross electricity generated.
Renewables as % of gross electricity consumption = 9.4%
CHP as % of total electricity generation = 6.2%

Figure 4: Breakdown of fuel consumption and electricity generated in Irish electricity system [14].

There is a second entry available for the Condensing section called PP2. This is usually used for the economic analysis if there is highly contrasting plant on the system: if there is one group of plants with a high efficiency but are expensive, and another group of plants which have a low efficiency but are cheap. Therefore, these may need to be analysed separately by the model.

3.1.1.3 Renewable Energy


EnergyPLAN 7.20: Startdata
File Edit Help
Frontpage Input Cost Regulation Output Settings
ElectricityDemand DistrictHeating RenewableEnergy Storage Cooling Individual Industry Transport Waste
Electricity production from Renewable Energy and Nuclear :
Renewable Energy Source
Capacity: MW
Stabilisation share
Distribution profile
Production TWh/year
Correction factor
Post Correction production
Change Wind 1000 0 Change Hour_wind_1.txt 2.07 0 2.07
Change Photo Voltaic 500 0 Change Hour_wind_1.txt 1.04 0 1.04
Change Wave Power 0 0 Change Hour_solar_prod1 0.00 0 0.00
Change River Hydro 0 0 Change Hour_solar_prod1 0.00 0 0.00
Hydro Power :
Capacity 0 MW-e
Efficiency 0.33
Storage 0 GWh
Pump Capacity 0 MW-e
Pump Efficiensy 0.9
Annual Water supply 0 TWh/year
Distribution of water Change Hour_wind_1.txt
Estimated anuual production: 0.00 TWh/year
Storage difference: 0 GWh
Geothermal Power
Capacity: 0 MW-e
Efficiency 0
Distribution: Change Hour_wind_1.txt
Annual production: 0.00 TWh/year
Hydro water
Hydro storage
Hydro PP
RES electricity
Geothermal power

Before explaining how I obtained the data, I would like to recall what parameters are required. In order to define the energy available from a renewable energy resource in your energy-system, you need to define five major features:

1. The type of renewable energy in question
2. The installed capacity of the renewable resource
3. The distribution profile (hourly for one year)
4. The stabilisation share
5. Correction factor

Parameters 1-3 are reasonably intuitive. Therefore, I will only recap on the 'stabilisation share' and the 'correction factor' here. So, just to repeat from the EnergyPLAN user manual [15], the stabilisation share is the percentage (between 0 and 1) of the installed capacity of the renewable resource that can contribute to grid stability i.e. provide ancillary services such as voltage and frequency regulation on the electric grid. At present renewable-energy technologies, with the exception of hydro plants with storage, cannot help regulate the grid. Therefore, the stabilisation share will be set to 0 unless this changes in the future.

Also from the EnergyPLAN user manual [15], the correction factor adjusts the hourly distribution inputted for the renewable resource. It does not change the power output at full-load hours or hours of zero output. However, it does increase the output at all other times. This can be used for a number of different reasons. For example, future wind turbines may have higher capacity factors, and thus the same installed wind-capacity will produce more power.

Onshore Wind

I obtained the installed wind-capacity and the hourly wind-output for 2007 from the Irish TSO. The stabilisation factor was inputted as 0 because wind power does not contribute to grid stabilisation. Also, the correction factor was inputted as 0 because the installed wind-capacity and the distribution used generated the expected annual wind-energy. Otherwise, the correction factor would need to be adjusted until the wind production calculated by the model was the same as the actual annual-production.

Offshore Wind

There was very little historical data available for offshore wind in Ireland. There is currently only one offshore wind farm constructed, which is located at Arklow Banks, off the coast of County Wicklow. This wind farm is using a new wind turbine developed by GE Energy, hence they will not release any information in relation to the power generated from the turbines. The only information I had was the installed capacity of the wind turbines: 25.2 MW (7 x 3.6 MW turbines). As a result I used the onshore wind-distribution that I had obtained from the Irish TSO, combined with the correction factor in EnergyPLAN. The reason the onshore wind-distribution is a good source of data, is because it accounts for the variations in wind speed over the island of Ireland. The only difference between onshore and offshore wind-distributions is the higher capacity-factor for offshore. This is accounted for by the correction factor in EnergyPLAN. However, after deciding to use the onshore wind-distribution, I then had to identify the annual wind energy produced by the 25.2 MW of offshore wind. I calculated this in two different ways.

For the first method I began by obtaining the average annual wind speed at location of the offshore wind farm (8.75 m/s), using the Irish wind atlas [16]. Then I got an annual offshore wind distribution from a data buoy located close to the offshore wind farm (data buoy M2 from [17]). This data had an average annual wind speed of 7.82 m/s over the year 2007. Therefore, I scaled-up this distribution curve until the average-annual wind-speed was 8.75 m/s (the same as the average wind speed at the offshore wind farm). Finally, I got the power curve for a Vestas V90 wind turbine as seen in Figure 5, and calculated the expected output for a single year from the offshore wind farm. I did not want to use the power curve for the GE Energy wind turbines which were installed at the offshore wind farm, as these are still at the testing stage. At this point I had calculated an expected offshore wind-production of 0.11 TWh: using the power curve and wind-speed distribution with

average annual wind speed of 8.75 m/s. Using the onshore wind-distribution, the annual electricity-generated from the 25.2 MW offshore wind farm was 0.07 TWh. However, from my calculations, the total electricity that should have been generated was 0.11 TWh. Consequently, I adjusted the 'Correction Factor' (to 0.65) until the total offshore wind output was 0.11 TWh. This accounted for the higher capacity factor of the offshore wind turbines in comparison to the onshore wind turbines. However, if 25.2 MW of wind power produced an annual output of 0.11 TWh, this would give the wind farm a capacity factor of 49.8% which is very high and hence I used a second method also.

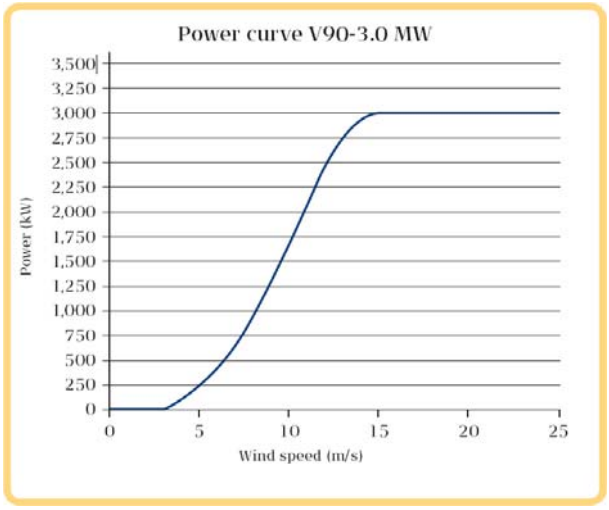


Figure 5: Vestas V90 Power Curve [18].

For the second method, I simply found the average capacity factor for an offshore wind farm in Ireland, which was 40% [19]. I then calculated the annual output from the wind farm, E_{Annual}, using the installed wind capacity, PW, and the average offshore wind farm capacity-factor, CF_W, as displayed below:

$$E_{Annual} = 8760 P_W CF_W \quad (2)$$

The result was 0.088 TWh from an installed wind capacity of 25.2 MW with a capacity factor of 40%. Therefore, after the offshore wind capacity and onshore wind-distribution were inputted into EnergyPLAN, and the correction factor was adjusted (to 0.36) until the annual output was 0.088 GWh. In my opinion, this method is better when simulating alternatives which introduce new large-scale wind capacities, as it uses the average capacity factor. In comparison, the first method is better if you are simulating a specific wind farm as it takes into account the specific wind speeds at that site. As Ireland has very little offshore wind at the moment, but my future alternatives will most likely simulate large-scale offshore wind capacities, I used the second method for my model.

Photovoltaic

There is currently no PV power installed in Ireland so no data was required for the reference model. However, this is discussed in Section 2 in relation to data for alternative models.

Tidal

There is currently no tidal power installed in Ireland so no data was required for the reference model. However, this is discussed in Section 2 in relation to data for alternative models.

Wave Power

There is currently no wave power installed in Ireland so no data was required for the reference model. However, this is discussed in Section 2 in relation to data for alternative models.

River Hydro

River hydro refers to hydroelectric dams with no storage facility i.e. they must operate as water passes through them. Although there is no river hydro in Ireland at the moment, it was used to simulate the Irish reference model. I found that if hydro power was simulated under the "Hydro" option, which discussed after this section, EnergyPLAN would optimise the dispatch of hydro itself. However, the optimal dispatch of hydro according to EnergyPLAN was different to the actual dispatch of hydro power in Ireland in the year 2007. In contrast, the river hydro power did not optimise the dispatch of hydro, but instead it replicated the historical hourly values that were inputted as the distribution. These hourly outputs were obtained from the Irish TSO, but note that it took four months to obtain this data so long waiting-periods may need to be accounted for. When modelling future alternatives for Ireland, I will use the Hydro Power option in EnergyPLAN, as this will enable EnergyPLAN to optimise the dispatch of hydro which is desirable in the future.

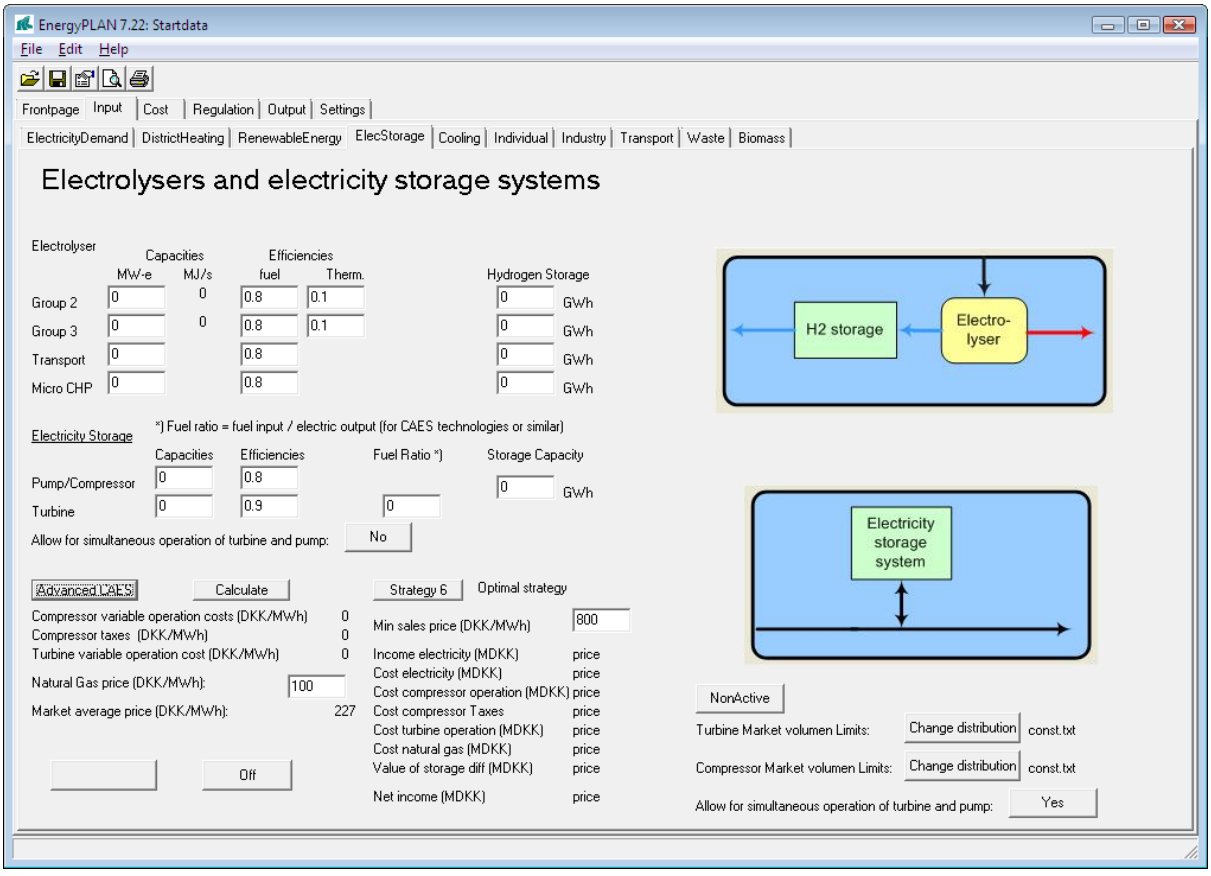
Hydro Power

I found that hydro data was quite difficult to gather i.e. power capacity and storage capacity. As indicated in Figure 4, hydro only provides 2.3% of Ireland's electricity demands, and therefore there is not a lot of detailed information which is easily accessible for the hydro plants. As a result, I found that the most productive approach was to contact the hydro plants directly, and request the data required from the operator in the control room. For the distribution of the hydro production, I used annual output data for the hydro plants which was recorded by the Irish TSO's, EirGrid [20] and SEMO [21]. As stated previously, hydro power was only simulated using this option when modelling future alternatives for Ireland, and not when modelling the reference model in 2007.

Geothermal / Nuclear

There is currently no geothermal or nuclear power-stations installed in Ireland so no data was required.

3.1.1.4 Electricity Storage

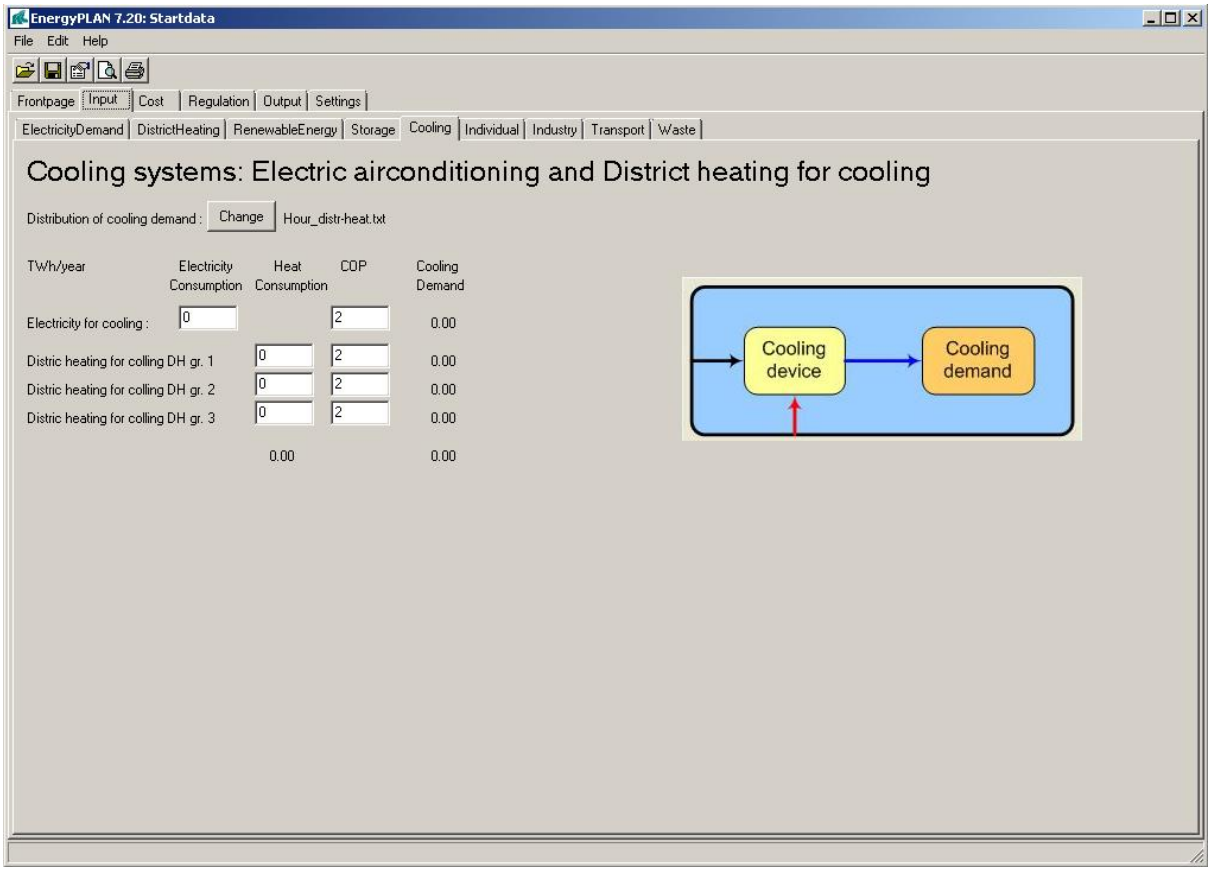


Only pumped-hydroelectric energy storage (PHES) is in use in Ireland so I did not have to gather any data on electrolysers or compressed-air energy storage (CAES). For the PHES parameters I simply contacted the plant control rooms and they provided information of pump/turbine and storage capacities. However, plant efficiencies could not be revealed as it was "commercially sensitive". Therefore, from the Energy Balance, I calculated the overall PHES efficiency using

$$\eta_{TH} = \frac{E_{OUT}}{E_{IN}} \tag{3}$$

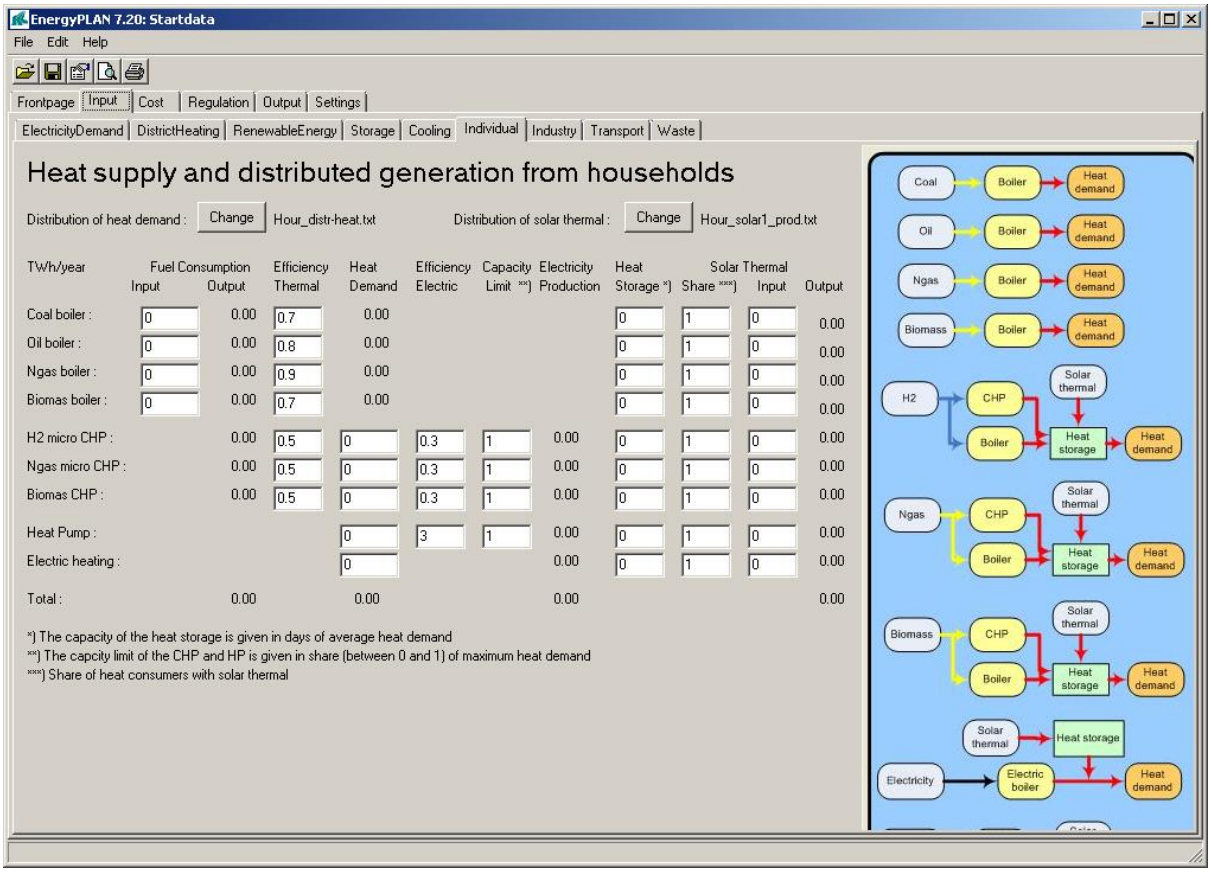
where E_{OUT} was the total electricity produced from Turlough Hill in 2007 (0.349 TWh) and E_{IN} is the total electricity consumed by Turlough Hill in 2007 (0.546 TWh). The resulting round-trip-efficiency, η_{TH}, was 63.9%. Therefore, I inserted the a pump efficiency of 79.9% and a turbine efficiency of 79.9%, so that the round-trip-efficiency was 0.799*0.799 = 0.639. Note that the same efficiency was used for the pump and turbine as this is typically the situation within a pumped-hydroelectric energy storage facility [22].

3.1.1.5 Cooling


EnergyPLAN 7.20: Startdata
File Edit Help
Frontpage Input Cost Regulation Output Settings
ElectricityDemand DistrictHeating RenewableEnergy Storage Cooling Individual Industry Transport Waste
Cooling systems: Electric airconditioning and District heating for cooling
Distribution of cooling demand : Change Hour_distr-heat.txt
TWh/year Electricity Consumption Heat Consumption COP Cooling Demand
Electricity for cooling : 0 2 0.00
Distric heating for colling DH gr. 1 0 2 0.00
Distric heating for colling DH gr. 2 0 2 0.00
Distric heating for colling DH gr. 3 0 2 0.00
0.00 0.00
Cooling device
Cooling demand

There is currently no cooling-load in Ireland so no data was required for the Irish reference-model. Note that the heat demand under the cooling tab is for absorption cooling.

3.1.1.6 Individual


EnergyPLAN 7.20: Startdata
File Edit Help
Frontpage Input Cost Regulation Output Settings
ElectricityDemand DistrictHeating RenewableEnergy Storage Cooling Individual Industry Transport Waste
Heat supply and distributed generation from households
Distribution of heat demand : Change Hour_distr-heat.txt
Distribution of solar thermal : Change Hour_solar1_prod.txt
TWh/year Fuel Consumption Input Output Efficiency Thermal Heat Demand Efficiency Electric Capacity Limit **) Electricity Production Heat Storage *) Solar Thermal Share ***) Input Output
Coal boiler :
Oil boiler :
Ngas boiler :
Biomas boiler :
H2 micro CHP :
Ngas micro CHP :
Biomas CHP :
Heat Pump :
Electric heating :
Total :
*) The capacity of the heat storage is given in days of average heat demand
**) The capcity limit of the CHP and HP is given in share (between 0 and 1) of maximum heat demand
***) Share of heat consumers with solar thermal
Coal
Oil
Ngas
Biomass
H2
Boiler
CHP
Solar thermal
Heat storage
Heat demand
Electricity
Electric boiler

Heat Distribution

It was very difficult to predict the annual heat distribution for the entire population of Ireland. In order to estimate it, I used 'Degree Day' data from Met Eireann, the Irish meteorological service [23].

There are Heating Degree-Days (HDD) and Cooling Degree-Days (CDD). As their title suggest, the HDD indicate the level of heating required on a given day, and the CDD indicate the level of cooling required on a given day. In Ireland, cooling is not required due to the climate, therefore, using the Heating Degree-Days indicate the amount of heat required could be estimated.

Heating Degree-Days work as follows: The temperature within a building is usually 2-3°C more than outside, so when the outside temperature is 15.5°C, the inside of a building is usually 17.5°C to 18.5°C. Therefore, once the temperature drops below this 15.5°C outside-temperature setpoint, the inside temperature drops below 17.5/18.5°C and the space heating within a building is usually turned on. Note that this 15.5°C setpoint is specifically for Ireland and it can change depending on a number of factors such as climate, house insulation etc [23]. A full explanation about the calculation and application of degree data can be obtained from [23, 24].

By obtaining the Heating Degree-Day data, the level of heat required each day within a building can be estimated. Consequently, an annual distribution of space-heating demand can be created with a resolution of 1 day (as Degree Day data is only recorded on a daily basis) as seen in Figure 6. For the EnergyPLAN model, hourly data is required so this 1 day data was converted into hourly readings using a computer program written in MATLAB: if you follow the same approach you can contact me to use the model at david.connolly@ul.ie. However, this only considered the space-heating distribution and not the hot-water distribution. Therefore, the heat distribution accounting for both space heating and hot-water demand had to be constructed.

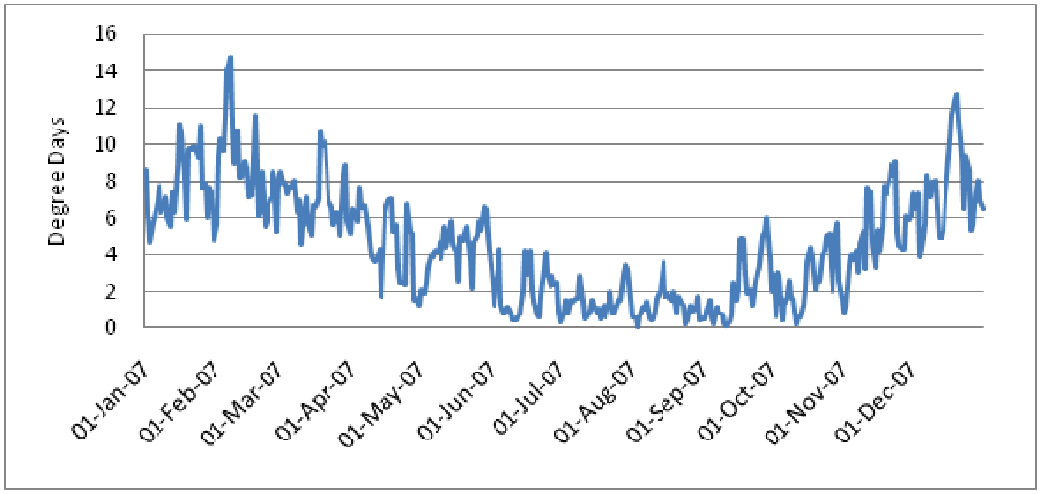


Figure 6: Degree Day data from Belmullet meteorological station in Mayo, Ireland.

For the summer months, it was assumed that space heating would not be required: it was assumed that the heat absorbed by the building during warm temperatures, and also the building's occupants, would keep the building warm during colder temperatures. Therefore, during the summer hot water is the only heating demand. It was also assumed that hot water is a constant demand each day for the entire year, as people tend to use a consistent amount of water regardless of temperature or time of year. The BERR in the UK completed a report in relation to domestic hot-water and space heating, which indicated that the ratio of space-heating to hot-water heating in the home is 7:3 [25]. Therefore, as seen in Figure 7, for the heat distribution a 30% constant bandwidth was placed at the base representing hot-water demand, and a 70% demand was placed on top (based on Degree Day data) representing the space-heating requirements. Figure 7 represents the heat distribution constructed for modelling the heat demand within the Irish energy-system.

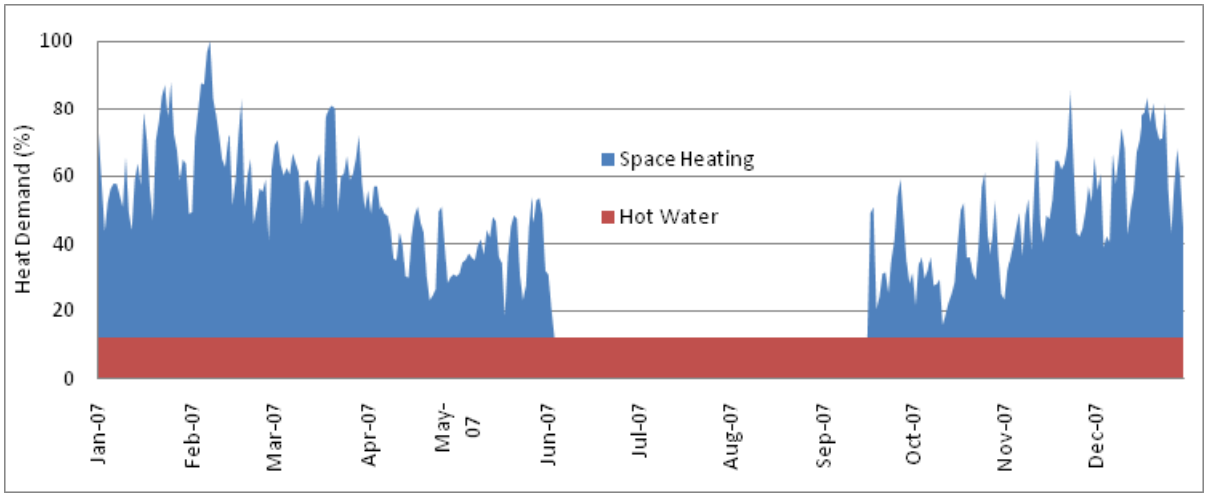


Figure 7: Individual heat distribution for Ireland.

Finally, the daily distribution created using the degree-day data had to be converted into hourly data for EnergyPLAN. To do this a daily cycle was applied to the distribution which is displayed in Figure 8. The daily cycle used was taken from a similar study completed on Denmark in [4]. It was assumed that Ireland would have a similar daily distribution for heat as Denmark.

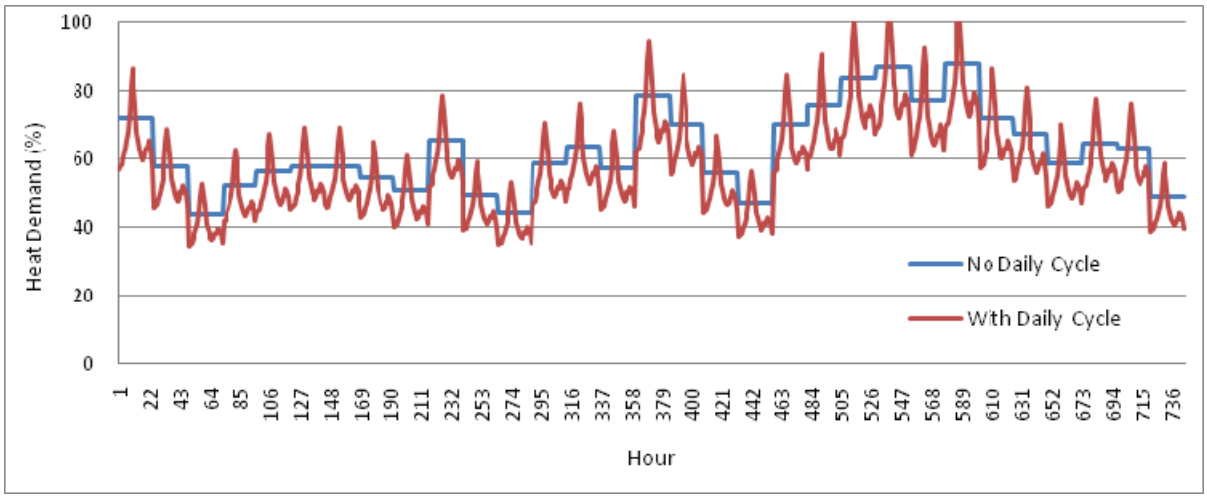


Figure 8: Individual heat-distribution for January 2007 in Ireland (Hourly).

Fuel Consumption and Efficiency of Boilers

The fuel consumed for residential heating can be obtained from the Energy Balance. For the boiler efficiencies, I consulted the Building Energy Rating documentation provided by the Irish energy agency, SEI [26]. This documentation is used by assessors to complete energy ratings for homes in Ireland. Therefore, the documentation gave the typical type and efficiency of different domestic boilers used in Ireland. This documentation is possibly available in other countries also, or if not, the efficiencies within this documentation could be applied to other applications.

Electric Heating

Electric heating demand can also be difficult to quantify as it is usually discussed in conjunction with the heating demand and not as a separate entity. From a report completed by the Irish energy agency, SEI, it was found that 14% of all domestic electricity is used for space heating and 23% for hot water [27]. In a separate report by SEI, it was found that 12% of commercial electricity was used for heating purposes [28]. Therefore, I used these figures to calculate the electric heating demand in Ireland i.e. (37% of domestic electricity plus 12% of commercial electricity).

Solar Distribution

There are two types of solar thermal in the EnergyPLAN model: Solar thermal that contributes to district heating and solar thermal for individual households. At present, only individual solar-thermal energy is used in Ireland and hence it is discussed in this section under the individual's heating-demands. The inputs required for the EnergyPLAN model are the:

1. The total solar-thermal-production for 2007
2. Hourly distribution of the solar-thermal production in 2007
3. Solar-thermal share

The total solar-production in Ireland for 2007 was got from the 2007 Energy Balance [29]. For the distribution, an attempt was made to obtain the hourly power-output from a solar panel for an existing installation[3] in Ireland, but this could not be obtained. As a result, the solar-thermal output curve that was constructed for Denmark was used, as the solar radiation in Denmark is very similar to the solar radiation in Ireland, as displayed in Figure 9. To ensure the Danish solar resource was similar to the Irish solar resource, global solar-radiation data was compared between Denmark and Ireland as seen in Table 3. It clearly verifies the similarity and therefore it was considered reasonable to assume that the solar-thermal output would be very similar for both Denmark and Ireland. This solar-thermal distribution was created by a Danish energy consultancy,

[3] Solar-thermal output can be found by measuring the inlet and outlet temperatures of the collector, and also the flow rate.

PlanEnergi [30] for the 2030 Danish Energy-Plan [3, 4]. The distribution gives the production of an individual-solar-thermal installation of 4.4 m^2 during a typical Danish year. The production is calculated on the basis of a consumption of 150 litres per day, heated from 10°C to 55°C in combination with a 200 litre storage tank. The 4.4 m^2 represents a solar-thermal installation designed for hot water and some contribution to space heating.

Table 3
Global solar-radiation in Denmark and Ireland.

Country	Number of Stations That Provided Data	Average-Annual Global-Solar-Radiation (kWh/m^2)
Denmark	4	976
Ireland	7	989

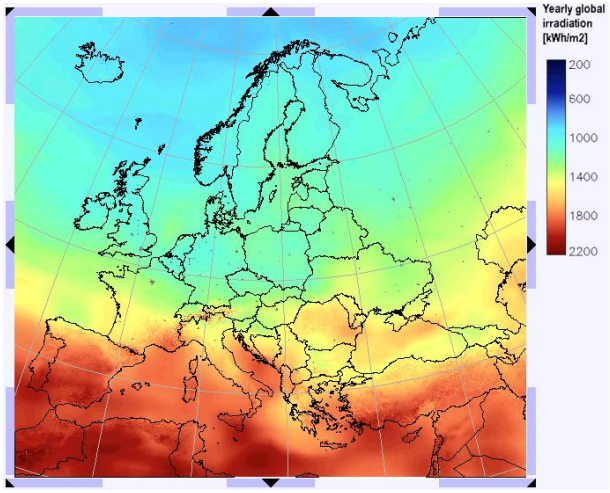


Figure 9: Solar radiation.

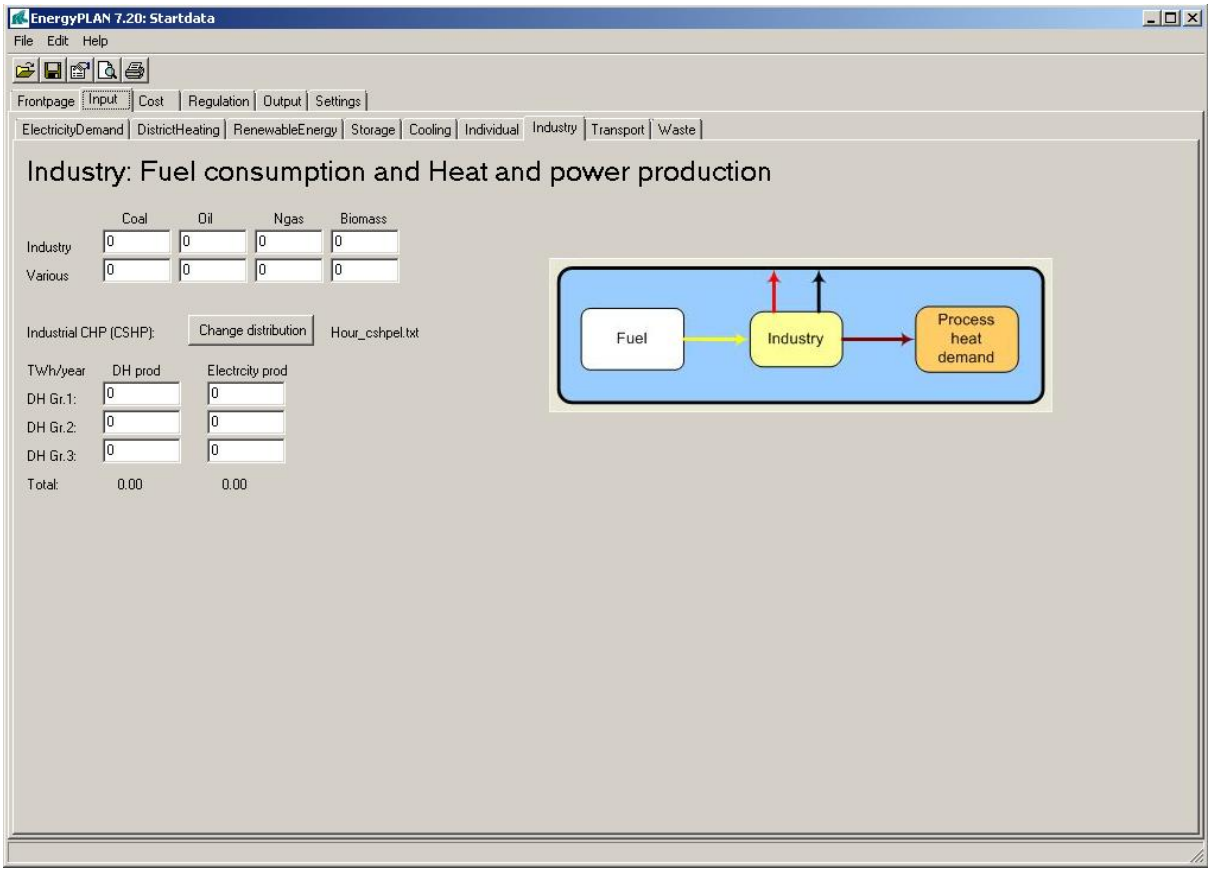
Solar Share

The solar share is the percentage of houses that have a solar panel installed: To estimate this in Ireland, I contacted the Irish energy agency, SEI [8], who told me that there was 33,600 m^2 of solar-thermal panels installed in Ireland. A typical solar-installation in Ireland uses 5 m^2, therefore it was assumed that there are approximately 6,720 solar installations in Ireland. From the 2006 census in Ireland, it was stated that there are 1,469,521 homes in Ireland [31]. Therefore, it was concluded that there is a solar-thermal installation in 0.45% (6720/1469521) of Irish houses.

Solar Input

As stated above, I found the total solar energy utilised from the Irish Energy-Balance [29]. The solar input and solar share can be adjusted until the solar production matches the value stated in the Energy Balance.

3.1.1.7 Industry



Fuel Consumption

The quantity of each fuel-type consumed within industry can be found in the Energy Balance [29]. The 'Various' input is only used when a consumption cannot be specified anywhere else or may need to be analysed on its own i.e. gas consumption for offshore drilling.

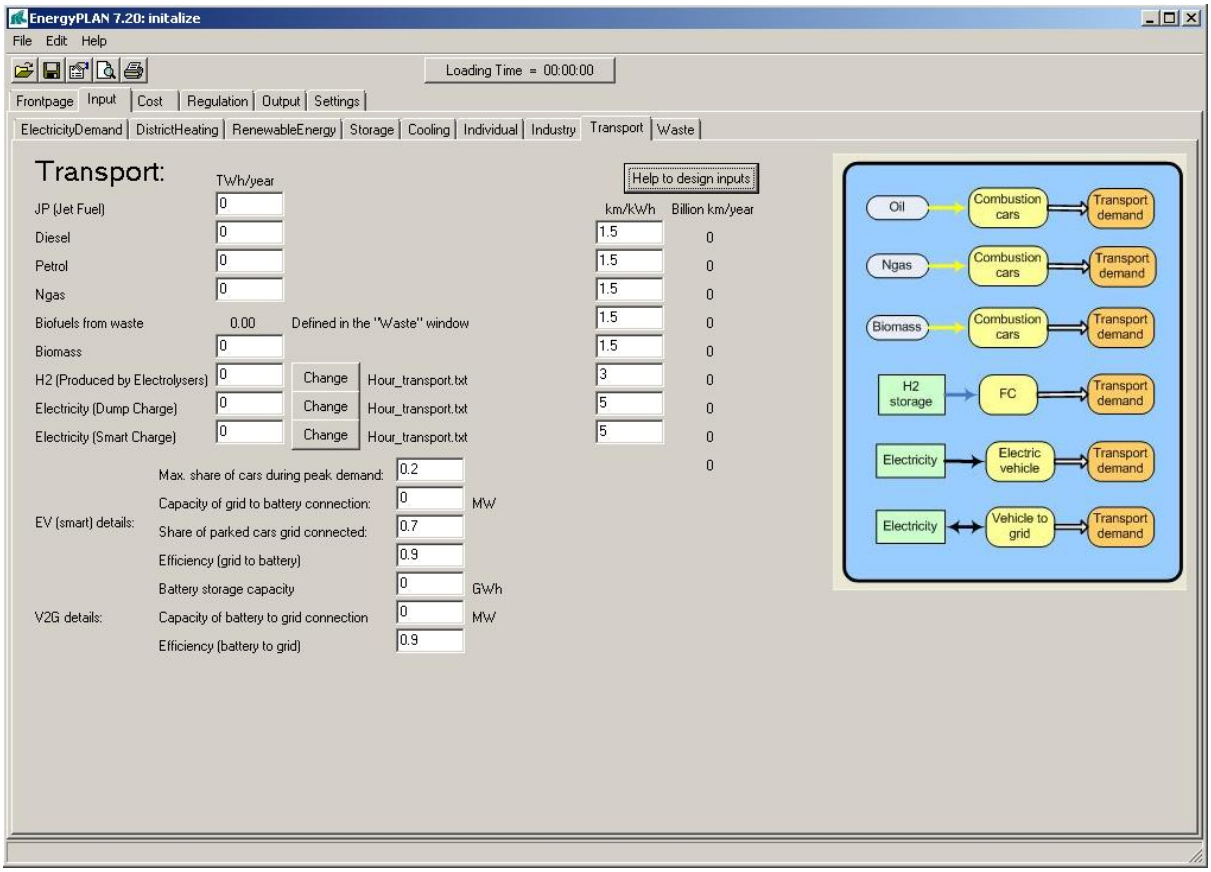
Industrial CHP: Energy Production

In order to quantify the capacity of industrial CHP, I had to contact the statistics department within the Irish energy agency, SEI, who had the breakdown of CHP plants at their disposal. They could identify from their records how much CHP in Ireland was industrial and how much was dispatchable. From this they could also provide the amount of electricity and heat that was produced from both industrial and dispatchable CHP.

Industrial CHP: Distribution

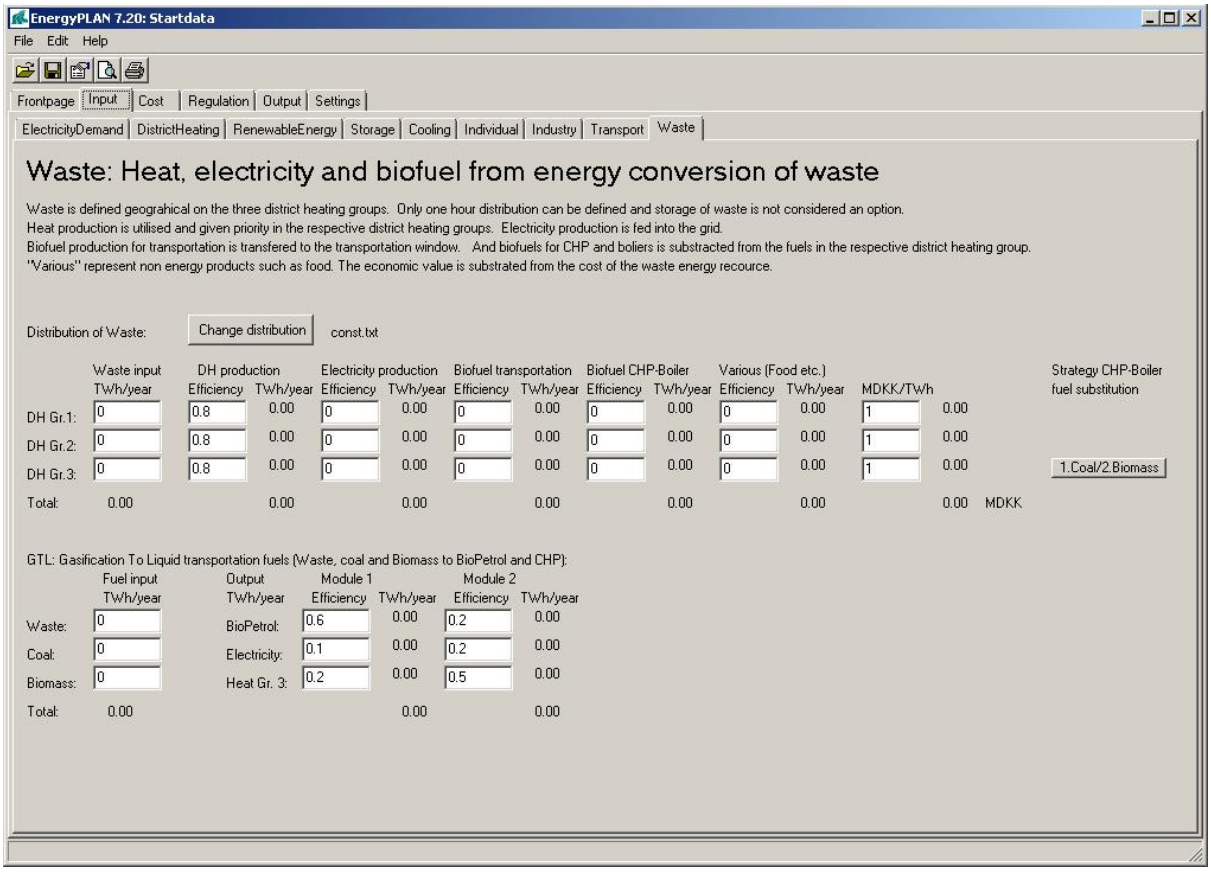
Since the industrial CHP in Ireland was not controlled by the TSO, this means that the distribution used for Industrial CHP was const.txt. This means that the output was simply constant. It is the best proxy for modelling a production that cannot be controlled.

3.1.1.8 Transport



The amount of fuel used for transport is also available from the Energy Balance [29].

3.1.1.9 Waste


EnergyPLAN 7.20: Startdata
File Edit Help
Frontpage Input Cost Regulation Output Settings
ElectricityDemand DistrictHeating RenewableEnergy Storage Cooling Individual Industry Transport Waste
Waste: Heat, electricity and biofuel from energy conversion of waste
Waste is defined geograhical on the three district heating groups. Only one hour distribution can be defined and storage of waste is not considered an option.
Heat production is utilised and given priority in the respective district heating groups. Electricity production is fed into the grid.
Biofuel production for transportation is transfered to the transportation window. And biofuels for CHP and boliers is substracted from the fuels in the respective district heating group.
"Various" represent non energy products such as food. The economic value is substrated from the cost of the waste energy recource.
Distribution of Waste:
Change distribution
const.txt
Waste input TWh/year
DH production Efficiency TWh/year
Electricity production Efficiency TWh/year
Biofuel transportation Efficiency TWh/year
Biofuel CHP-Boiler Efficiency TWh/year
Various (Food etc.) Efficiency TWh/year
MDKK/TWh
Strategy CHP-Boiler fuel substitution
DH Gr.1:
DH Gr.2:
DH Gr.3:
Total:
MDKK
1.Coal/2.Biomass
GTL: Gasification To Liquid transportation fuels (Waste, coal and Biomass to BioPetrol and CHP):
Fuel input TWh/year
Output TWh/year
Module 1 Efficiency TWh/year
Module 2 Efficiency TWh/year
Waste:
Coal:
Biomass:
BioPetrol:
Electricity:
Heat Gr. 3:
Total:

There is currently no waste used for energy production in Ireland so no data was required for the Irish reference-model.

3.2 Data for Future-Alternatives with a Technical Optimisation

Once the reference model is completed, a number of new technologies can be introduced. Below is a description of the inputs used in the first alternatives analysed for the Irish energy-system.

3.2.1 Photovoltaic

As I could not obtain PV output from Ireland, I used the results obtained from a Danish project called Sol300: As discussed previously, the solar-radiation available in Ireland and Denmark is very similar (see Table 3). This project involved the installation of grid-connected PV-panels on 300 homes in Denmark and the corresponding output was recorded. This output is discussed in [6], and is available in the Distributions folder that comes with the EnergyPLAN model. The name of the distribution is hour_PV_eltra2001 and hour_PV_eltra2002, for the years 2001 and 2002 respectively.

Work is currently underway to find a relationship between PV output and global solar-radiation (as global solar-radiation is the most common form of measuring solar radiation at meteorological stations). This section will be updated when this work is completed.

3.2.2 Tidal

Tidal power is developing rapidly at present. It is very similar to most renewable-energy as you must use it when it is being generated. However, the unique characteristic of tidal power is the fact that it can be predicted in advance: on a minute resolution, at least three years in advance, if not more. In order to simulate tidal power, I sourced two studies completed in Ireland: one by SEI (the Irish Energy Authority), titled "Tidal and Current Energy Resources in Ireland" [32], and one by the Department of Communications, Energy and Natural Resources called "All-Island Grid-Study: Renewable Energy Resource Assessment (Workstream 1)" [33]. The first study [32] identified viable tidal-energy resource available in Ireland from tidal power (0.92 TWh), and the second study [33] created a power-output curve for tidal devices as seen in Figure 10. Using these two inputs it was possible to simulate tidal energy in EnergyPLAN. It is worth noting that these figures were based on 'first-generation tidal-devices', so the area investigated came under the following restrictions:

1. Water depth between 20m and 40m
2. Sites outside major shipping lanes
3. Sites outside military zones and restricted areas
4. Sites which do not interfere with existing pipelines and cables
5. 12 nautical mile limit offshore
6. Peak tidal velocity greater than 1.5m/s

'Second-generation tidal-devices' are expected to be developed that can be placed in areas without some of these restrictions (see Figure 11). However, these devices are not expected until 2015 [33].

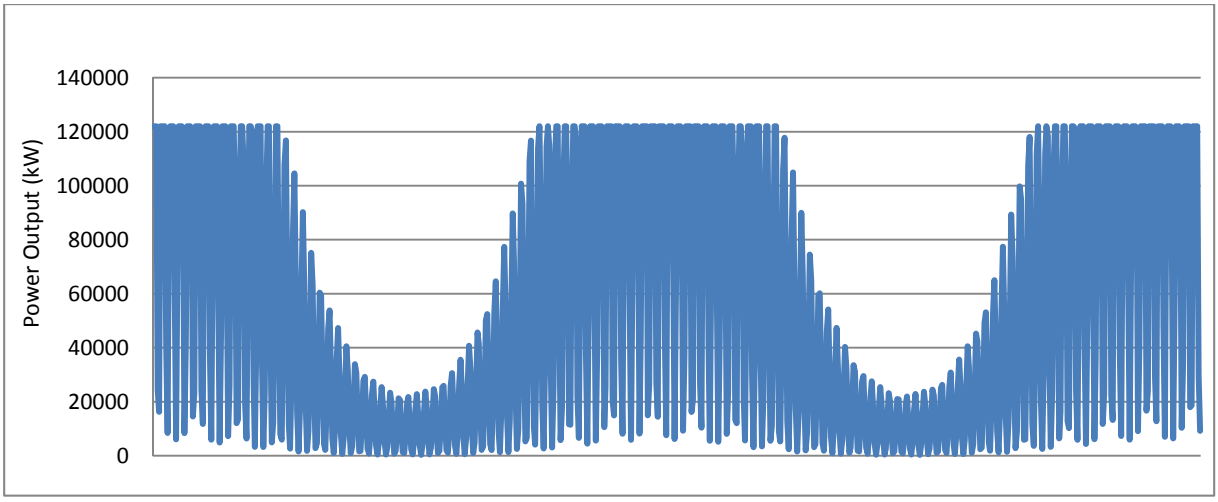


Figure 10: Tidal Output for January from a 122 MW Tidal-Farm [33].

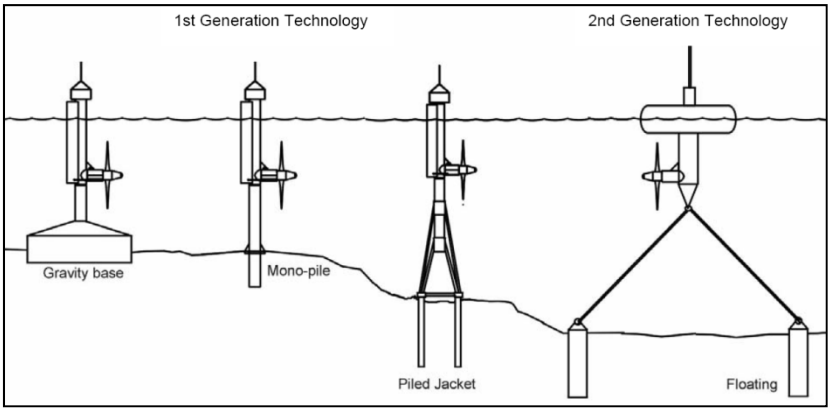


Figure 11: First and Second generation tidal technology [34].

3.2.3 Wave Power

I consulted with Jens Peter Kofoed (Aalborg University) in order to generate the expected wave power data for my model. During our discussion, it became apparent that the future of wave power is very unclear.

Unlike wind power where the three-bladed design has become the primary turbine, there will be no standard design for future wave generators. This is due to the fact that wave power depends on two parameters: wave height and wave period. Different wave generators will be used depending on the specific wave height and period characteristics at the sites. It is unlikely that any single wave generator will be the most efficient at all sites.

The most convincing way to predict the wave-power contribution for an energy-system in the future is to use the output from a wave generator device that is publicly providing a power matrix, particularly the Pelamis, see Figure 12a. The Pelamis power matrix (as illustrated in Figure 12b) is available to the public and hence can be used in conjunction with wave-height and wave-period data to predict future wave power. Since I created the wave-power output I have also found two other wave-power matrices: one for the Wave Dragon (see Figure 13) and the other for the Archimedes (see Figure 14).

Significant wave height (H_{sig}, m) \ Power period (T_{pow}, s)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

(a) **(b)**

Figure 12: Pelamis wave-generator (a) and power-matrix: output in kW (b).

Significant Wave Height - m \ Wave Period – Tz (s)	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	203	276	348	432	516	608	699	798	896	925	953	958	962	941	919	870	820	742	663	555	446
1.5	412	448	485	617	750	899	1049	1212	1375	1433	1491	1509	1527	1502	1477	1404	1332	1209	1086	912	737
2.0	621	621	621	802	983	1191	1398	1626	1853	1941	2029	2061	2092	2063	2034	1939	1844	1677	1509	1269	1028
2.5	1123	1123	1123	1213	1304	1609	1914	2258	2602	2752	2903	2972	3041	3017	2993	2868	2743	2504	2266	1910	1555
3.0	1624	1624	1624	1624	1624	2027	2430	2890	3350	3563	3776	3883	3989	3970	3951	3796	3641	3332	3022	2552	2082
3.5	2581	2581	2581	2581	2581	2783	2984	3588	4191	4494	4796	4870	4945	4935	4926	4845	4765	4374	3983	3372	2761
4.0	3538	3538	3538	3538	3538	3538	3538	4285	5032	5424	5816	5858	5900	5900	5900	5895	5889	5416	4943	4191	3439
4.5	4719	4719	4719	4719	4719	4719	4719	5093	5466	5662	5858	5879	5900	5900	5900	5897	5895	5658	5422	4822	4222
5.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5452	5004
5.5	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5676	5452
6.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
6.5	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
7.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
7.5	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900
8.0	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900	5900

Figure 13: Wave Dragon Power Matrix (optimised for high average wave conditions): output in kW [35].

Significant Wave Height Hsig - m \ Wave Period – Tpow (s)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5	18.0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	2	7	13	19	26	34	41	48	58	68	81	93	105	118	131	144	153	163	183	203	213	223	223	223	223	225	227
1.5	4	15	28	41	56	72	85	99	121	143	173	203	226	248	266	285	309	334	357	380	389	398	398	398	398	403	409
2.0	8	26	49	73	100	127	150	172	210	247	292	337	366	395	418	442	482	523	543	563	579	596	596	596	596	597	598
2.5	15	43	78	113	159	205	234	263	320	376	438	499	531	563	603	643	675	708	741	774	785	797	797	797	797	800	804
3.0	25	61	111	161	227	293	339	386	453	521	600	680	722	765	827	888	897	906	945	984	996	1009	1009	1009	1009	1003	998
3.5	35	92	155	218	305	391	454	517	605	694	772	851	913	975	1036	1096	1119	1141	1163	1185	1198	1211	1211	1211	1211	1208	1206
4.0	35	114	194	273	380	486	572	659	776	894	961	1027	1103	1179	1227	1275	1316	1357	1365	1374	1394	1414	1414	1414	1414	1415	1416
4.5	0	0	235	332	479	626	722	819	957	1096	1168	1240	1320	1401	1449	1497	1547	1598	1590	1583	1610	1637	1637	1637	1637	1616	1595
5.0	0	0	280	400	592	784	899	1014	1144	1274	1380	1487	1569	1651	1691	1731	1785	1838	1807	1777	1806	1836	1836	1836	1836	1806	1777
5.5	0	0	320	432	641	849	1033	1216	1331	1446	1568	1690	1778	1867	1919	1970	1977	1984	1994	2005	2017	2030	2030	2030	2030	1990	1951
6.0	0	0	0	0	680	944	1155	1367	1495	1623	1759	1895	1983	2072	2137	2202	2205	2207	2226	2246	2240	2234	2234	2234	2234	2194	2154
6.5	0	0	0	0	720	1123	1335	1547	1678	1809	1963	2116	2200	2284	2332	2380	2425	2470	2452	2434	2403	2373	2373	2373	2373	2354	2336

Figure 14: Archimedes-Wave-Swing Power-Matrix (unrestricted): output in kW [35].

When multiple power matrices are available, the suitability of the device for a particular site can be evaluated by completing a scatter diagram. The wave height and wave period recorded at the site in question should be plotted against one another as illustrated in Figure 15. If the power matrix and recorded data from the site in question overlap each other significantly on the scatter diagram, then the wave energy generator being investigated is a good choice for that particular location. As seen in Figure 15, the Pelamis is a very good match for the sample site analysed.

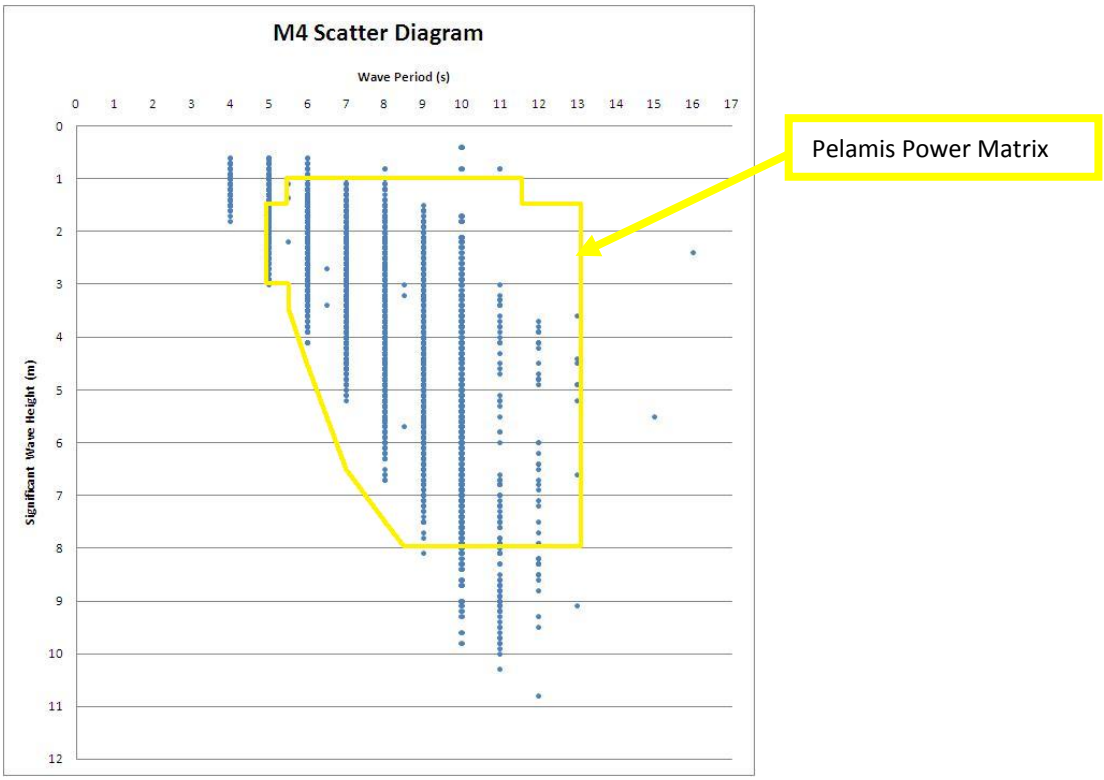


Figure 15: Scatter diagram for M4 data buoy off the coast of Ireland.

Once the most suitable wave power device has been chosen, and the power matrix obtained, the wave-height and wave-period data recorded at the site must be converted into power output. To do this, I have created a program using MATLAB which can be obtained by contacting me at david.connolly@ul.ie.

For my particular study, I used wave-height and wave-period data from four different sites around the coast of Ireland. The data was gathered by the Marine Institute in Ireland using data buoys (see Figure 16) distributed around the Irish coast [36]. Obtaining data from four different locations spread over each corner of the island, ensured that wave energy fluctuations were minimised. A list of data buoys can be seen at [37].

Figure 16: A Data Buoy.

3.2.4 Future Additions

A number of other technologies will be analysed in upcoming alternatives for the Irish energy-system so the input details will be added in due course.

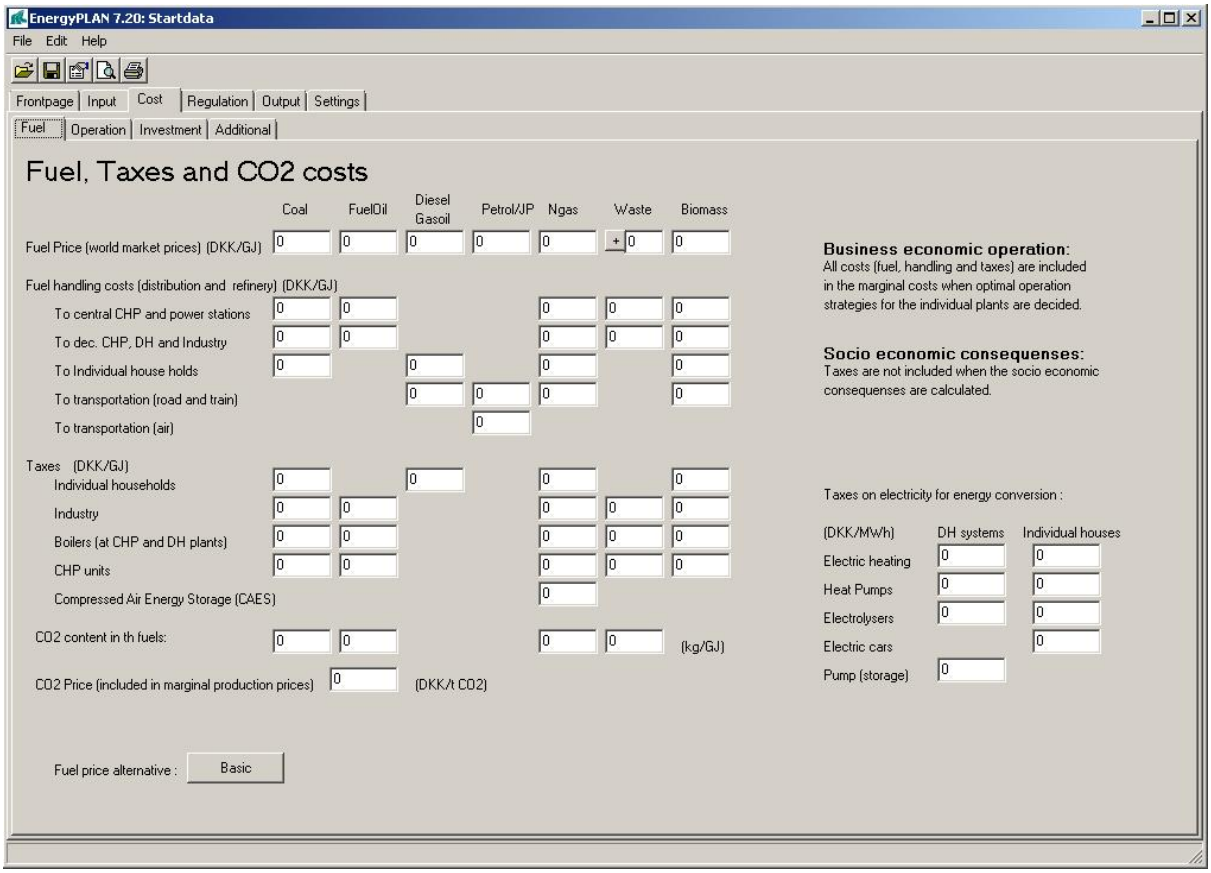
3.3 Data for Costs

EnergyPLAN simulates the costs of an energy-system in four primary categories:

1. Fuel costs: purchasing, handling and taxes in relation to each fuel as well as CO_2 costs
2. Investment costs: capital required, the lifetime of each unit and the interest rate on repayments
3. Operation costs: the variable and fixed operation and maintenance costs for each production unit
4. Additional costs: any extra costs not accounted for in the program by default e.g. the cost of insulating houses for increased energy efficiency. This was not used to create the 2007 Irish energy-system but may be used for future scenarios.

These costs are used by EnergyPLAN to perform socio-economic and business-economic studies, as well as a market optimisation for the energy-system.

3.3.1 Fuel Tab


EnergyPLAN 7.20: Startdata
File Edit Help
Frontpage Input Cost Regulation Output Settings
Fuel Operation Investment Additional
Fuel, Taxes and CO2 costs
Coal FuelOil Diesel Gasoil Petrol/JP Ngas Waste Biomass
Fuel Price (world market prices) (DKK/GJ)
Fuel handling costs (distribution and refinery) (DKK/GJ)
To central CHP and power stations
To dec. CHP, DH and Industry
To Individual house holds
To transportation (road and train)
To transportation (air)
Taxes (DKK/GJ)
Individual households
Industry
Boilers (at CHP and DH plants)
CHP units
Compressed Air Energy Storage (CAES)
CO2 content in th fuels:
(kg/GJ)
CO2 Price (included in marginal production prices)
(DKK/t CO2)
Fuel price alternative :
Basic
Business economic operation:
All costs (fuel, handling and taxes) are included in the marginal costs when optimal operation strategies for the individual plants are decided.
Socio economic consequenses:
Taxes are not included when the socio economic consequenses are calculated.
Taxes on electricity for energy conversion :
(DKK/MWh) DH systems Individual houses
Electric heating
Heat Pumps
Electrolysers
Electric cars
Pump (storage)

3.3.1.1 Fuel and CO_2 Costs

The purchasing costs for each fuel were obtained for the year 2007, 2010/2015 and 2020, which were recommended by the International Energy Agency [38] and the Danish Energy Authority [39] and are displayed in Table 4. Also, if required the current market price for different fuels can be obtained from the links below:

- Crude Oil: http://www.oil-price.net/
- Coal: http://www.eia.doe.gov/cneaf/coal/page/coalnews/coalmar.html
- Natural Gas: http://www.bloomberg.com/markets/commodities/energyprices.html

Table 4
Fuel prices used for 2007, 2010/2015 and 2020 [38, 39].

(€/GJ)	Crude Oil ($/bbl)	Crude Oil	Fuel Oil	Gas Oil/ Diesel	Petrol/JP	Coal	Natural Gas	Biomass
2007	69.33	9.43	6.66	11.79	12.48	1.94	5.07	6.30
2010/2015	100	13.60	9.60	17.00	18.00	3.19	8.16	7.01
2020	110	14.96	10.56	18.70	19.80	3.11	9.16	7.45

The crude oil price was used to identify the cost of Fuel Oil, Diesel and Petrol / Jet Fuel. As these fuels are refined from crude oil their prices are proportional to the crude oil price and hence, the price ratio between each of these and crude oil typically remains constant. Therefore, the following ratios recommended by the Danish Energy Authority was used to calculate these prices [39]: ratio of crude oil to fuel oil was 1 to 0.70, crude oil to diesel was 1 to 1.25, and crude oil to petrol/jet fuel was 1 to 1.33. Also, the fuel handling costs were obtained from the Danish Energy Agency [39] and are displayed in Table 5.

Table 5
Fuel handling costs [39].

€/GJ	Fuel Oil	Gas oil/Diesel	Petrol/JP	Coal	Natural Gas	Biomass
Power Stations (central)	0.228	0.228	-.-	0.067	0.428	1.160
Distributed CHP, district heating & industry	1.914	1.807	-.-	-.-	1.165	1.120
Individual households	-.-	2.905	-.-	-.-	2.945	6.118
Road transport	-.-	3.159	4.257	-.-	-.-	11.500 [40]
Airplanes	-.-	-.-	0.696	-.-	-.-	-.-

3.3.1.2 Taxes

I rang the Irish revenue office to find out if there were any taxes on specific fuels or technologies and found that there was none. Note that Value Added Tax (VAT) is not included here.

3.3.1.3 CO_2 Content

In the EnergyPLAN model, three CO_2 emission factors are required: one for coal, oil and natural gas. However, in this study coal and oil do not just account for a single fuel but instead, they account for a group of fuels. The coal category represents peat and coal as were modelled as a single fuel: this is a method which has been carried out in previous models of the Irish energy-system [41] due to the similar power-plant efficiencies and CO_2 emissions of the two fuels. The oil category represents a number of different types of oil including kerosene, diesel, coke etc. Therefore, the CO_2 emission factors for coal and oil were calculated based on fuel consumptions from the Irish energy-balance [29], and CO_2 emission factors recommended by SEI [14] for the various fuel they represent. In conclusion, the CO_2 emission factor used for coal/peat was 100.63 kg/GJ (see Table 6), for oil was 73.19 kg/GJ (see Table 7) and for natural gas was 57.1 kg/GJ [14].

Table 6
CO_2 emission factor for coal/peat.

Fuel	Consumption (TWh) [29]	Consumption (% of Total)	CO_2 Emission Factor (kg/GJ) [14]
Coal	17.425	65.09	94.60
Milled Peat	6.186	23.11	116.70
Sod Peat	2.167	8.09	104.00
Briquetted Peat	0.992	3.71	98.90
Total	**26.770**	**100.00**	**100.63**

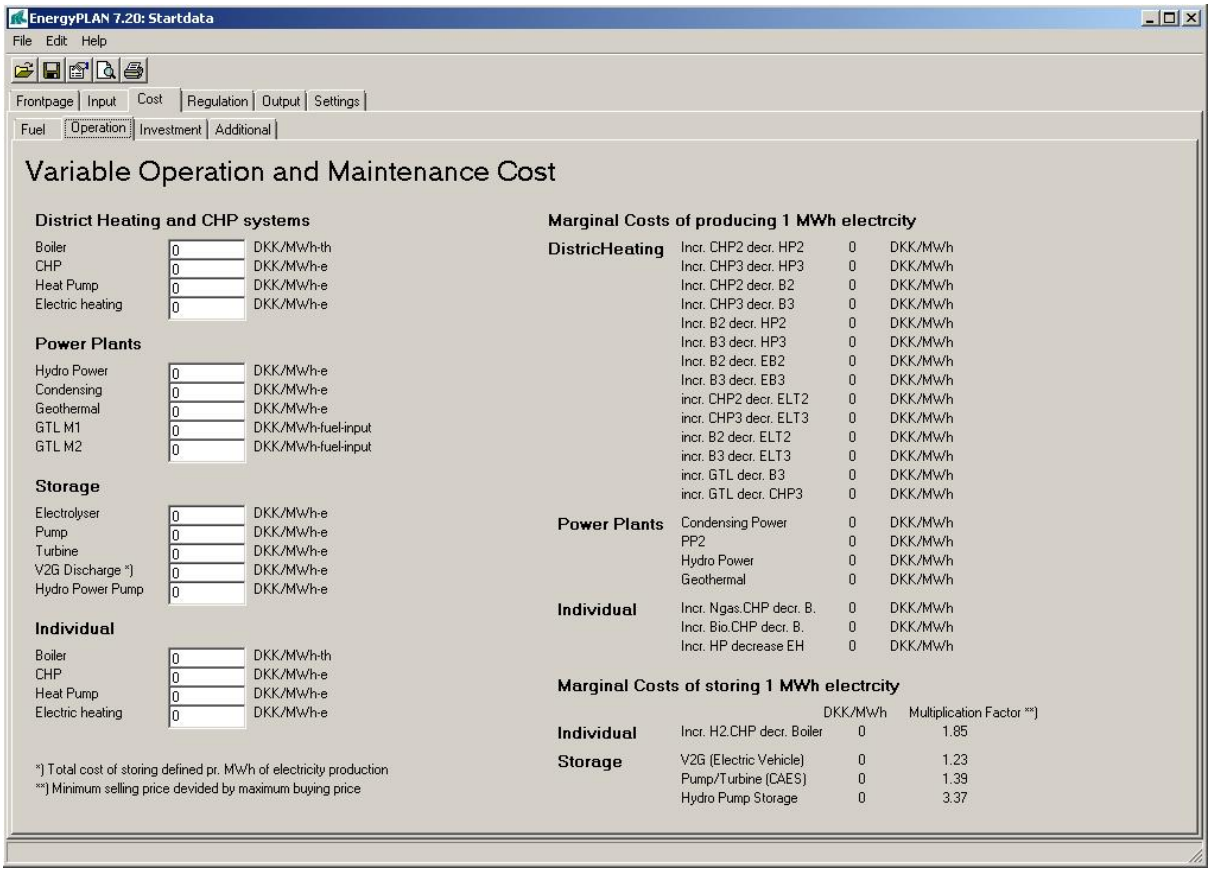
Table 7
CO_2 emission factor for oil.

Fuel	Consumption (TWh) [29]	Consumption (% of Total)	CO_2 Emission Factor (kg/GJ) [14]
Gasoil	45.230	43.35	73.3
Gasoline	17.425	21.40	70.0
Jet Kerosene	12.134	11.63	71.4
Kerosene	10.620	10.18	71.4
Fuel Oil (Residual Oil)	8.528	8.17	76.0
Coke	3.637	3.49	100.8
LPG	1.856	1.78	63.7
Naphtha	0.012	0.01	73.3
Total	**104.342**	**100.00**	**73.2**

3.3.1.4 CO_2 Price

There is no carbon tax in Ireland at the moment. However, Ireland participates in the European carbon trading scheme and therefore there is a cost associated with carbon, even though it is not an internal government tax. For information on carbon costs, visit http://www.pointcarbon.com/.

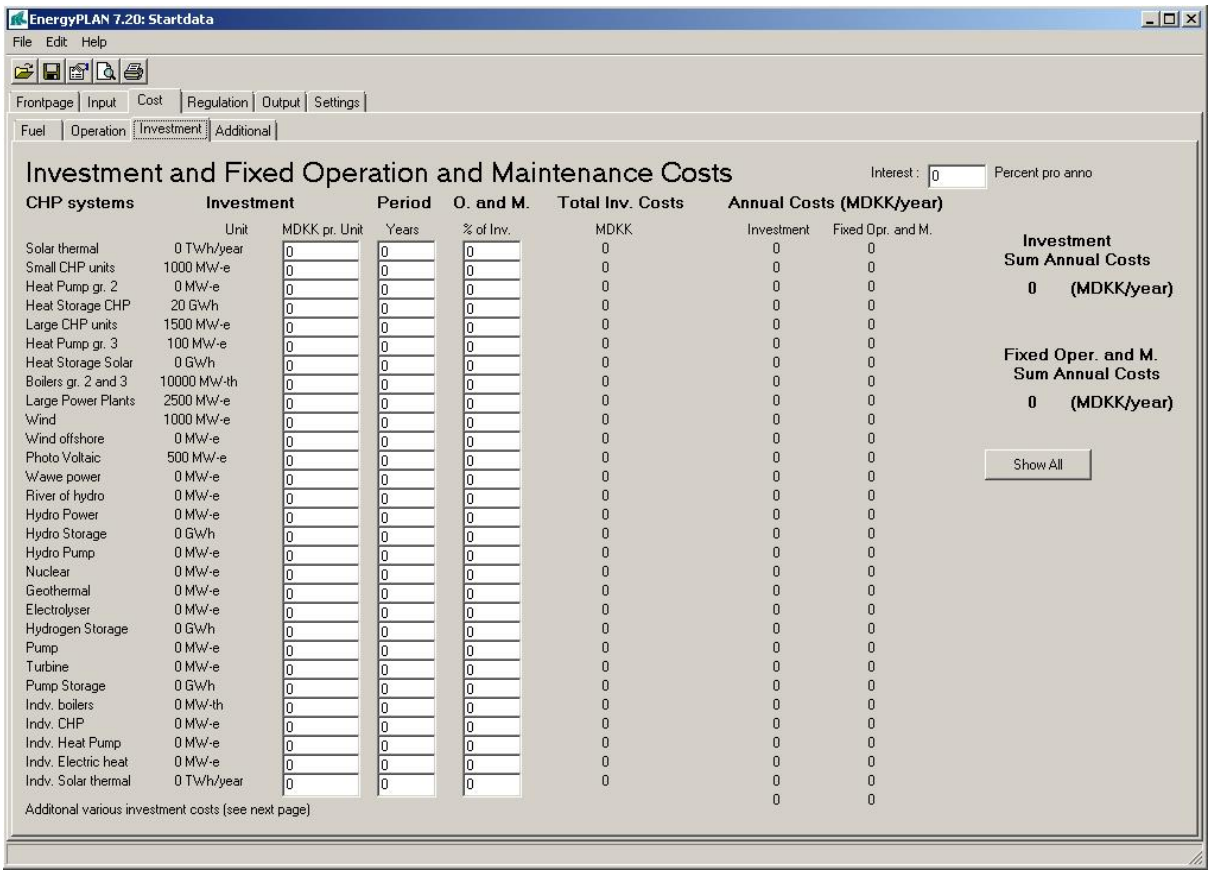
3.3.2 Operation Tab


EnergyPLAN 7.20: Startdata
File Edit Help
Frontpage Input Cost Regulation Output Settings
Fuel Operation Investment Additional
Variable Operation and Maintenance Cost
District Heating and CHP systems
Boiler 0 DKK/MWh-th
CHP 0 DKK/MWh-e
Heat Pump 0 DKK/MWh-e
Electric heating 0 DKK/MWh-e
Power Plants
Hydro Power 0 DKK/MWh-e
Condensing 0 DKK/MWh-e
Geothermal 0 DKK/MWh-e
GTL M1 0 DKK/MWh-fuel-input
GTL M2 0 DKK/MWh-fuel-input
Storage
Electrolyser 0 DKK/MWh-e
Pump 0 DKK/MWh-e
Turbine 0 DKK/MWh-e
V2G Discharge *) 0 DKK/MWh-e
Hydro Power Pump 0 DKK/MWh-e
Individual
Boiler 0 DKK/MWh-th
CHP 0 DKK/MWh-e
Heat Pump 0 DKK/MWh-e
Electric heating 0 DKK/MWh-e
*) Total cost of storing defined pr. MWh of electricity production
**) Minimum selling price devided by maximum buying price
Marginal Costs of producing 1 MWh electrcity
DistricHeating
Incr. CHP2 decr. HP2 0 DKK/MWh
Incr. CHP3 decr. HP3 0 DKK/MWh
Incr. CHP2 decr. B2 0 DKK/MWh
Incr. CHP3 decr. B3 0 DKK/MWh
Incr. B2 decr. HP2 0 DKK/MWh
Incr. B3 decr. HP3 0 DKK/MWh
Incr. B2 decr. EB2 0 DKK/MWh
Incr. B3 decr. EB3 0 DKK/MWh
incr. CHP2 decr. ELT2 0 DKK/MWh
incr. CHP3 decr. ELT3 0 DKK/MWh
incr. B2 decr. ELT2 0 DKK/MWh
incr. B3 decr. ELT3 0 DKK/MWh
incr. GTL decr. B3 0 DKK/MWh
incr. GTL decr. CHP3 0 DKK/MWh
Power Plants
Condensing Power 0 DKK/MWh
PP2 0 DKK/MWh
Hydro Power 0 DKK/MWh
Geothermal 0 DKK/MWh
Individual
Incr. Ngas.CHP decr. B. 0 DKK/MWh
Incr. Bio.CHP decr. B. 0 DKK/MWh
Incr. HP decrease EH 0 DKK/MWh
Marginal Costs of storing 1 MWh electrcity
DKK/MWh Multiplication Factor **)
Individual
Incr. H2.CHP decr. Boiler 0 1.85
Storage
V2G (Electric Vehicle) 0 1.23
Pump/Turbine (CAES) 0 1.39
Hydro Pump Storage 0 3.37

Under this tab you must enter the variable operation and maintenance costs. These are the costs that occur if the technology in question is used. For example, an annual service has to be done every year regardless of how often the generating plant operates. Therefore, this is a fixed operation and maintenance charge. However, if the generating plant generates 1 GWh it must get a second service costing €1500. Therefore, the generating plant has a variable operation and maintenance cost of €1500/GWh or €1.50/MWh, as this second service will only be necessary if the plant actually operates.

For the condensing plant, I found the variable operation and maintenance costs for each type of power plants from [42], and calculated an overall variable O&M cost of 1.84 €/MWh as displayed in Table 8. For the pumped-hydroelectric energy storage (PHES) facilities, I obtained the variable operation and maintenance costs from [43], and to date I have not found the variable operation and maintenance cost for the individual units.

3.3.3 Investment Tab


EnergyPLAN 7.20: Startdata
File Edit Help
Frontpage Input Cost Regulation Output Settings
Fuel Operation Investment Additional
Investment and Fixed Operation and Maintenance Costs
Interest : 0 Percent pro anno
CHP systems Investment Period O. and M. Total Inv. Costs Annual Costs (MDKK/year)
Unit MDKK pr. Unit Years % of Inv. MDKK Investment Fixed Opr. and M.
Solar thermal 0 TWh/year
Small CHP units 1000 MW-e
Heat Pump gr. 2 0 MW-e
Heat Storage CHP 20 GWh
Large CHP units 1500 MW-e
Heat Pump gr. 3 100 MW-e
Heat Storage Solar 0 GWh
Boilers gr. 2 and 3 10000 MW-th
Large Power Plants 2500 MW-e
Wind 1000 MW-e
Wind offshore 0 MW-e
Photo Voltaic 500 MW-e
Wawe power 0 MW-e
River of hydro 0 MW-e
Hydro Power 0 MW-e
Hydro Storage 0 GWh
Hydro Pump 0 MW-e
Nuclear 0 MW-e
Geothermal 0 MW-e
Electrolyser 0 MW-e
Hydrogen Storage 0 GWh
Pump 0 MW-e
Turbine 0 MW-e
Pump Storage 0 GWh
Indv. boilers 0 MW-th
Indv. CHP 0 MW-e
Indv. Heat Pump 0 MW-e
Indv. Electric heat 0 MW-e
Indv. Solar thermal 0 TWh/year
Additonal various investment costs (see next page)
Investment Sum Annual Costs
0 (MDKK/year)
Fixed Oper. and M. Sum Annual Costs
0 (MDKK/year)
Show All

Under this tab you must enter the investment, lifetime and fixed operation and maintenance costs. These costs are used for to calculate the annual costs of each component. The investment and operation costs for condensing power-plants were obtained from [42], and are displayed in Table 8.

Table 8
Investment, fixed O&M and variable O&M costs for Irish condensing power-plants [42].

Plant Type	Investment Costs (M€/MW)	Fixed O&M Costs (€/MW/year)	Variable O&M Costs (€/MWh)	2007 Irish Capacity / Fuel Type
Steam turbine, coal fired, advanced steam process, 2004	1.100	16000	1.800	852.5 MW / Coal 806 MW / Oil
Steam turbine, coal fired advanced steam process, 20% co-firing of biomass, 2004	1.200	22000	3.000	345.6 MW / Peat
Gas turbine single cycle, (40 - 125 MW), 2004	0.485	7350	2.500	719 MW / Gas
Gas turbine combined cycle (100 - 400 MW), 2004	0.525	14000	1.500	2806 MW / Gas
Gas turbine combined cycle (10 – 100 MW), 2004	0.700	10000	2.750	208 MW / Gas

The onshore wind and offshore wind costs were obtained from [44]: investment costs for onshore wind are 1.2 M€/MW and offshore wind is €1.6 M€/MW, while the fixed O&M costs are 6 €/MWh for onshore wind and 8.70 €/MWh for offshore wind[4]. The investment costs for the hydro power in Ireland were obtained from the British Hydropower Association [45]: the investment cost for hydro stations below 100 MW is 1.765 M€/MW, the fixed O&M costs are approximately 2.7% of the investment and the variable O&M costs are approximately 1.3% of the investment. The costs for pumped-hydroelectric energy storage in Ireland were found from Gonzalez *et al.* [43] as €0.473.6 M€/MW and €7.89 / GWh for the initial investment, 3,000 €/MW for the fixed O&M cost and 3 €/MWh for the variable O&M cost.

For the individual heating-units (such as boilers, electric heaters, solar) I found the investment and fixed O&M costs by contacting the suppliers as displayed in Table 9.. Remember to include the installation costs for boiler and solar systems (i.e. plumbing and storage). The type of individual heating systems in Ireland (by fuel type) was got from a report carried out by the Irish Central Statistics Office (CSO) [46]. Finally, just to note that taxes should not be included in the costs inputted here. Therefore, if a supplier is contacted to obtain the costs, ensure the price quoted is without tax.

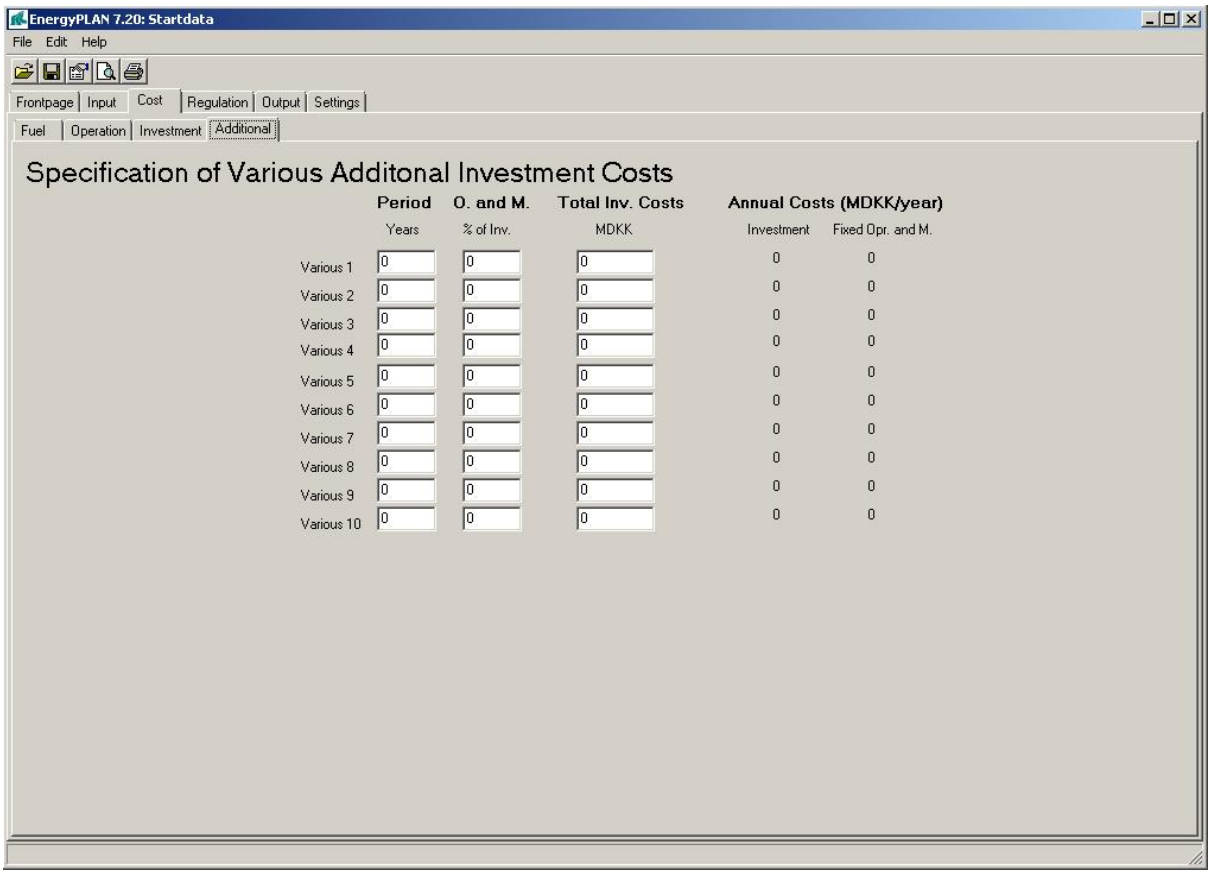
Table 9
Costs (excluding taxes) of individual heating-systems for the reference model of the Irish energy-system.

Fuel Type	Size	Cost Including Installation (€)	Lifetime (years)	O&M Costs (€/year)
Oil	26 kW	14750	15	110
Biomass	19 kW	19500	15	110
Natural Gas	26 kW	14750	15	110
Solid Fuel	21 kW	15300	15	110
Electric Boiler	12 kW	15500	15	0
Electric Heaters	20 kW	6000*	20	0
Solar Thermal	2400 kWh/year	5900	35	55

***Does not account for electric transmission upgrades that may be necessary for widespread installations**

[4] This does not include the balancing costs associated with wind power.

3.3.4 Additional Tab



This can be used if there is any additional costs which have not been accounted for. For example, the cost of insulating houses to reduce energy demands may be accounted for here.

4 Areas of Difficulty

Although a large degree of EnergyPLAN is intuitive, there were some areas which I found difficult to understand at first. Therefore, a few aspects of the model are discussed in more detail here.

4.1 Thermal Energy System

Coming from a country very little CHP plants or district heating exist, and the fact that heat is usually generated at the point of demand, I did not fully understand how a thermal energy system worked. As EnergyPLAN can model this type of energy system, a brief outline is provided. To illustrate the flexibility induced by thermal energy storage on such a system, a snapshot of the power production during different scenarios is presented below. The system in question contains a CHP plant, wind turbines, a thermal storage, a hot-water demand, and an electrical demand as illustrated in Figure 17.

During times of low wind-power, a lot of electricity must be generated by the CHP plants to accommodate for the shortfall power production. As a result, a lot of heat is also being produced from the CHP plant as seen in Figure 17a. The high production of heat means that production is now greater than demand, and consequently, heat is sent to the thermal storage.

Conversely, at times of high wind-power, the CHP plants produce very little electricity and heat. Therefore, there is now a shortage in of heat so thermal storage is used to supply the shortfall, as seen in Figure 17b.

Note: This system can be simulated by choosing the Technical Optimisation 2: Balancing Heat and Electricity Demands under the Regulation tab in EnergyPLAN.

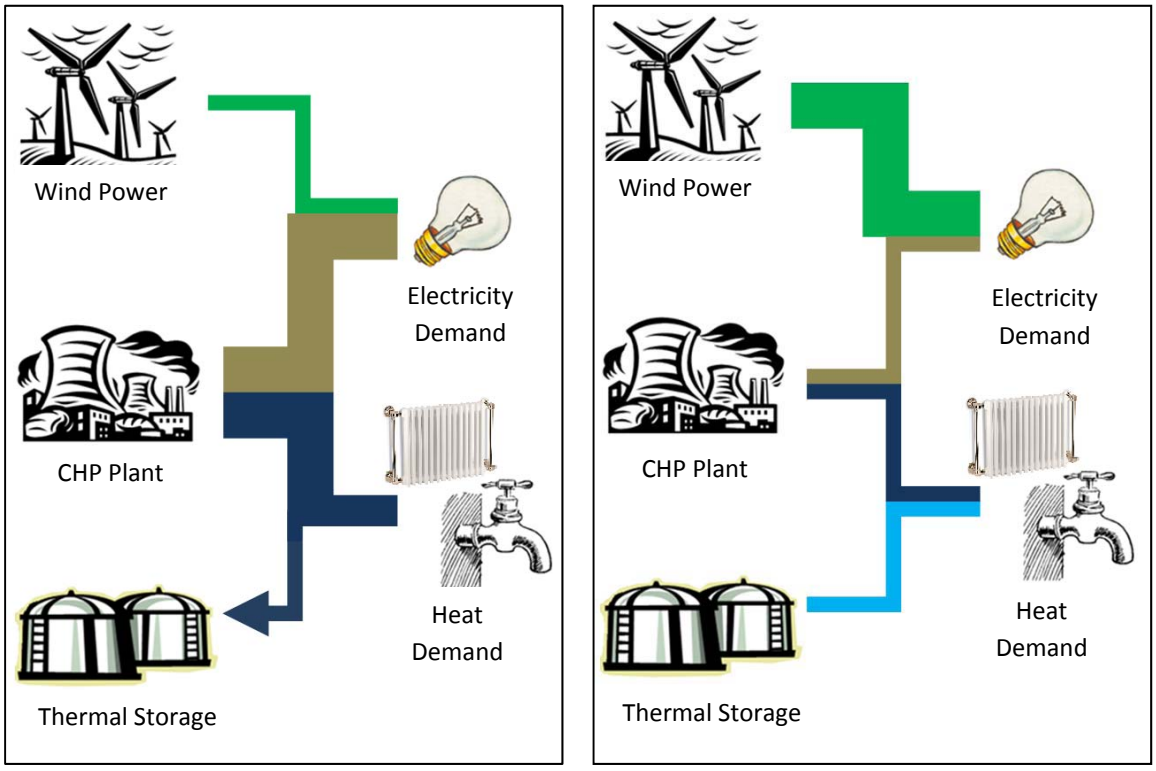


Figure 17: Energy-system with district heating and thermal energy storage during (a) a low-wind scenario and (b) a high-wind scenario.

This system has been put into practice in Denmark which has the highest wind penetration in the world. Also, Lund has outlined a roadmap for Denmark to use this setup in achieving a 100% renewable energy-system [4].

4.2 District Heating Groups

After learning about the operation of the thermal-storage energy-system, the next question that comes to mind is in relation to the CHP inputs under the 'Input -> DistrictHeating' tab. Under this tab there are three district-heating (DH) categories:

1. DH without CHP: These are systems that use boilers, waste heat or some other form of heat supply but do not use CHP. It is necessary to have this group in order to specify the heat capacity that is not going to be met by CHP plants.
2. DH with small CHP-plants: This category needs to be specified as they cannot operate without a heat load.
3. DH with large CHP-plants: This category specifies the amount of centralised CHP capacity. The primary difference between these and group 2, is the fact that these plants do not need to create heat during the production of electricity. They can remove the heat from their system using water (usually from a river or the sea).

4.3 Technical Optimisation vs. Market Optimisation

There are two kinds of studies that can be carried out in EnergyPLAN:

1. Technical Optimisation (tries to minimise fossil-fuel consumption and can be carried out without any cost inputs)
2. Market Optimisation (tries to minimise the operation costs of the system)

The technical optimisation is based on the technical abilities of the components within the energy-system. The difference between demand and supply is met as long as the power-producing units are capable of completing the task. Only in situations where the power-producing units are not able to meet demand is power imported from the external market, and where excess energy is produced (i.e. during high wind-speeds) energy is exported to the external market. There are four types of technical optimisation:

1. Balancing Heat Demands: This option performs a technical optimisation where heat-producing plants must operate according to the heat demand. The units chosen to supply the heat demand are chosen in the following order:
    a. Solar Thermal
    b. Industrial CHP
    c. Heat Production from Waste
    d. CHP Heat
    e. Heat Pumps
    f. Peak-Load Boilers

    This also affects electricity production: Under this regulation, the amount of heat that CHP units produce, and hence the amount of electricity they produce is dependent on the heat demand at that time.
2. Balancing Both Heat and Electricity Demands: This option performs a technical optimisation where CHP plants must operate according to the electricity demands, but the heat demands are still met by using thermal storage, heat pumps[5], and boilers. Hence the heat and electricity produced from the CHP plants at any time is dependent on the electricity demand. A graphical illustration of this option is displayed in Figure 17.

[5] Heat pumps are powered by electricity to transfer heat from one heat source (i.e. ground or water) into another heat source (i.e. a district-heating network).

3. Option 2 but "Reducing CHP also when partly needed for grid stabilisation": As stated this is largely the same as option 2. In option 2, CHP is reduced when there is a large output from renewable energy-sources. However, in option 3, CHP is also reduced if it is required for grid stabilisation[6].
4. Option 1 using the Triple Tariff: As stated this is largely the same as option 1. However, in this option, CHP plants do not operate according to the heat demand, but instead they operate according to the 'Triple Tariff'. The Triple Tariff was introduced in Denmark to encourage CHP units to produce electricity during peak hours. Therefore, CHP plants got paid 3 times more for producing electricity during peak hours (times) than any other time of the day. As a result, thermal storage became very common with CHP plants, so they could store the excess heat created while output was high during peak-electricity hours. This regulation option is used to simulate the Triple Tariff.

The market optimisation is designed to match supply and demand at the least cost, rather than on the minimum fuel consumption. For this optimisation two primary steps are completed:

1. The short-term marginal-cost[7] of producing electricity and/or heat is calculated for each power-producing unit
2. The least-cost combination of production units is chosen to supply the demand

For a detailed explanation of the calculations completed in both the technical optimisation and the market optimisation, read chapter 6 and 7 respectively in the EnergyPLAN user-manual [15].

4.3.1 Business-economic vs. Socio-economic calculations

The model distinguishes between two types of costs:

1. Business-Economic costs: Taxes are included
2. Socio-Economic costs: Taxes are not included

The socio-economic studies are designed to minimise the costs to society i.e. the cost for the region/country to provide the energy necessary. In a socio-economic study the aim is to identify the costs associated with the Technical Optimisation. This way you can optimise the performance of the energy-system without the restrictions imposed by economic infrastructures. Therefore, the following steps can be followed:

1. Complete a Technical Optimisation identifying the optimum technical-operation of the energy-system, for example the system with minimum Critical Excess Electricity Production (CEEP) or minimum CO_2.
2. Complete a socio-economic study to identify the costs associated with the technical optimisation

The business-economic studies show what can be done while being profitable for a business or person. Once the socio-economic study is completed, the market-economic study should be done to identify how the existing market-infrastructure obstructs the optimal technical-solution. Therefore, after completing steps 1 and 2 above:

3. Carry out a business-economic market-optimisation to identify how the existing system prevents the introduction of the optimal technical-solution.
4. Make changes to the existing tax system to outline how the existing market could be adjusted to promote the optimal technical-solution.

Sometimes, socio-economic costs can include the following aspects also:

1. Job Creation
2. Balance of Payment[8]

[6] The electric grid needs to be maintained at a certain frequency and voltage. Power plants usually provide ancillary services that ensure this frequency and voltage are maintained. If the frequency or voltage is not maintained, the electric grid will stop working.
[7] Marginal Cost: Is the cost at which there is enough supply to meet demand
[8] http://en.wikipedia.org/wiki/Balance_of_payments

3. Public Finances
4. Environmental Costs

However, these calculations are not made by the EnergyPLAN model. Instead, these benefits must be calculated externally based on the investments made in the different energy-system-sectors. These calculations are discussed further in [47].

4.4 Optimisation criteria for an Energy-System

It is very important to know how EnergyPLAN identifies that one energy-system is better than an alternative energy-system. There five primary variables that are recorded when doing this are:

1. PES (Primary Energy Supply): This is the total energy required within the energy-system
2. CO_2: This is the amount of CO_2 produced within the energy-system
3. Annual costs: The annual costs required to supply the required energy demand
4. EEEP (Exportable Excess Electricity Production): This is the amount of electricity that had to be exported from the energy-system, AND it was possible to export because the required transmission out of the energy-system was available.
5. CEEP (Critical Excess Electricity Production): This is the amount of electricity that had to be exported from the energy-system, BUT could NOT be exported because the required transmission was NOT available.

How important each of these parameters is depends on the objective of your study. Exercise four in the EnergyPLAN training (which is available from the EnergyPLAN website [1]) provides a good example of how these parameters are used to compare alternative energy-systems. Finally, other parameters may also be used to compare energy-systems, but these are the most common.

4.5 External Electricity Market Price

Under the regulation tab, an external electricity-market-price can be defined. The distribution is NOT indexed like other distributions in EnergyPLAN: instead the actual values in the distribution are used. The distribution can be manipulated by an 'Addition Factor' and a 'Multiplication Factor'. The addition factor is used to represent the cost of CO_2. If the CO_2 cost was increased or introduced in the external electricity-market, it would raise the cost of electricity by a constant amount for each hour. – Check Graphs in Excel sheet before explaining.

4.6 Operation Strategy for Electricity Storage

In EnergyPLAN, electricity storage is described in the form of pumped hydroelectric energy storage (PHES) as this is the largest and most common form of electricity storage in use today [48]. However, this can be used to define any type of electricity storage which has a charging capacity (i.e. pump/compressor), discharge capacity (i.e. turbine), and a storage capacity. When defining the electricity storage capacities available, it is also possible to define an electricity storage operation strategy. Once again, as EnergyPLAN uses PHES as a reference, the question asked in EnergyPLAN when defining an operation strategy is "Allow for simultaneous operation of turbine and pump: YES/NO", which is displayed in Figure 18.

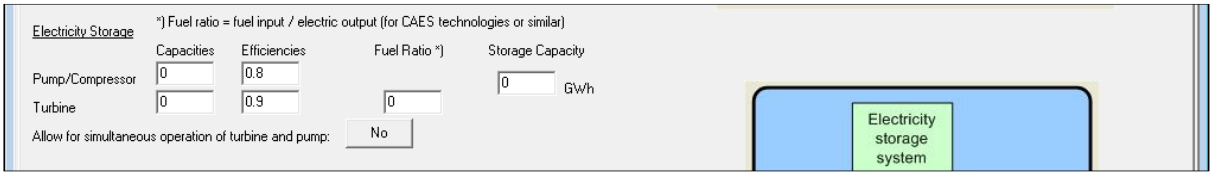


Figure 18: Electricity storage parameters and operation strategy in EnergyPLAN.

Historically, PHES (and other large-scale electricity storage) facilities have typically been constructed with a single penstock-system as they were designed to maximise electricity generation from baseload power-plants i.e. by charging during the night when electricity prices were low (due to a high percentage of baseload power)

and discharging during the day when electricity prices were high (due to a high demand). Therefore, they could not, or never needed to, charge and discharge at the same time. To simulate this scenario in EnergyPLAN, select NO for "Allow for simultaneous operation of turbine and pump". However, if energy storage devices are designed especially to integrate fluctuating renewable energy, there may be additional benefits when using PHES that can charge and discharge at the same time. This can be achieved in a single PHES facility by installing two penstocks, as displayed in Figure 19, or also by installing multiple single penstock-system PHES facilities on the same energy-system i.e. one can charge while the other is discharging at the same time. By using a double penstock-system, the PHES introduces more flexibility onto the energy-system and hence it can aid the integration of more renewable energy. As a result, this operation strategy is also possible in EnergyPLAN by selection YES when asked "Allow for simultaneous operation of turbine and pump".

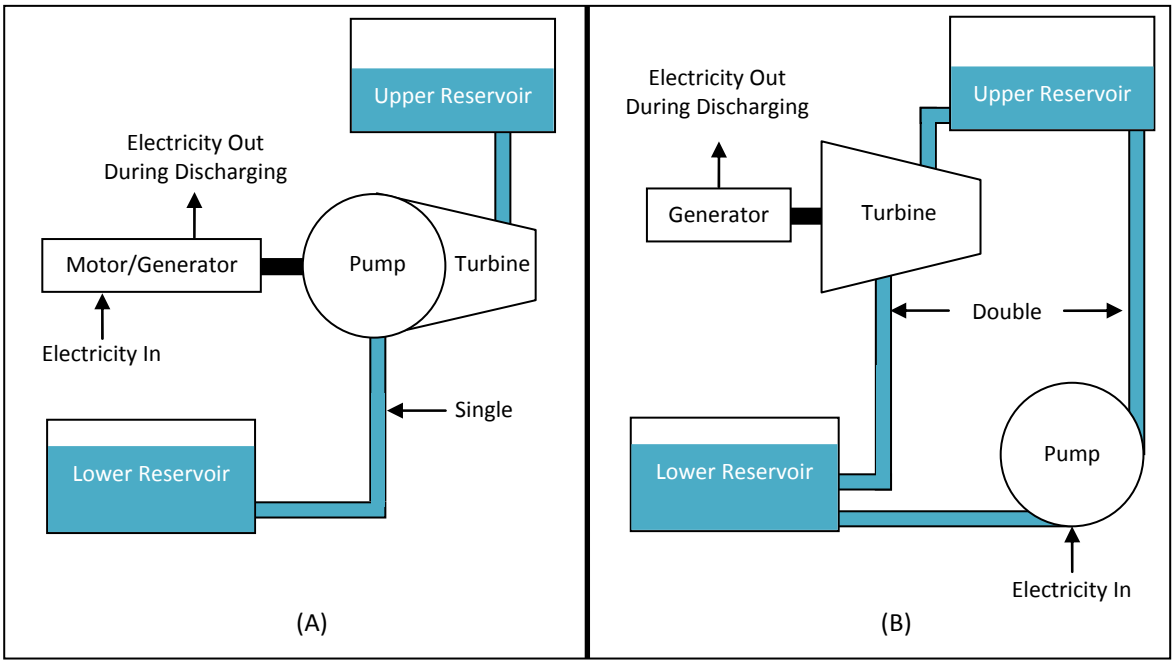


Figure 19: One PHES facility with (A) a single penstock-system and (B) a double penstock-system.

So how do these operation strategies affect the hourly operation of the system in EnergyPLAN? To illustrate this, an example is presented in Table 10 using the parameters defined in Table 11. As seen in Table 10, the primary advantage of a double penstock PHES facility relates to grid stabilisation: to see how the grid stabilisation percentage is calculated, see section 8.3 of the EnergyPLAN user manual. As the pump and turbine can operate together, a double penstock-system can store excess wind production using the pump, while also producing grid stabilising power using the turbine. In contrast, the single penstock-system has to prioritise one of these as the pump and turbine cannot operate together. From Table 10 it is clear that the single penstock-system prioritises the pump and therefore, the excess electricity is sent to the PHES while the power-plants (PP) must now provide the grid stabilising power. As a result, a system with single penstock PHES facility typically requires more fuel (i.e. more PP production) than a system with a double penstock PHES. Also, as a double penstock can charge and discharge at the same time, the storage capacity does not fill up as quickly as a single penstock-system. Therefore, double penstock-system can achieve higher fluctuating renewable energy penetrations at lower storage capacities than a single penstock-system.

Table 10
Results for hours 1-10 when using a single and a double penstock PHES operation strategy in EnergyPLAN.

hour	elec. demand	wind power	pp	pump	turbine	storage	stab. -load	import	CEEP	EEEP
Double Penstock-System: YES										
1	397	194	0	0	203	136	170	0	0	0
2	374	266	1	6	113	0	100	0	0	0
3	362	400	38	209	134	0	100	0	0	0
4	346	522	0	400	224	40	100	0	0	0
5	**331**	**750**	**0**	**740**	321	**230**	**100**	**0**	**0**	**0**
6	323	616	0	557	264	346	100	0	0	0
7	326	618	0	557	265	460	100	0	0	0
8	335	860	0	893	369	714	100	0	0	0
9	346	772	0	757	331	906	100	0	0	0
10	354	672	0	606	288	1031	100	0	0	0
Single Penstock-System: NO										
1	397	194	0	0	203	4747	170	0	0	0
2	374	266	114	6	0	4752	100	0	0	0
3	362	400	171	209	0	4919	100	0	0	0
4	346	522	224	101	0	5000	100	0	298	0
5	331	750	0	0	321	4598	100	0	740	0
6	323	616	264	502	0	5000	100	0	55	0
7	326	618	0	0	265	4669	100	0	557	0
8	335	860	369	414	0	5000	100	0	479	0
9	346	772	0	0	331	4586	100	0	757	0
10	354	672	288	517	0	5000	100	0	89	0

Table 11
Parameters used in EnergyPLAN for the sample calculations on the two PHES operation strategies.

Parameter	Capacity*
Electricity demand	4 TWh
Condensing power-plants	500 MW
Wind energy	2000 MW
Pump capacity	1000 MW
Turbine capacity	1000 MW
Pump efficiency	0.8
Turbine efficiency	0.8
Storage capacity	5 GWh
Regulation: Minimum grid stabilisation share	0.3 (i.e. 30%)

***All values were entered using the default distributions provided when opening EnergyPLAN**

4.6.1 Storage capacity for the double penstock-system strategy

It should be noted that when using a double penstock-system, the storage capacity may never be defined as full on an hourly value. This is due to the calculation procedure in EnergyPLAN. As stated previously, a double penstock-system can charge using excess electricity, while also discharging to provide grid stabilisation. Therefore, at the beginning of each hour EnergyPLAN must decide how much energy will be stored due to excess electricity and how much will be discharged to provide grid stabilisation. To do this the following sequence is used by EnergyPLAN:

1. The amount of excess wind power can be stored is calculated i.e. is there enough pump capacity and storage capacity available to send the excess electricity
2. It calculates the electricity that needs to be discharged to meet the grid stabilisation requirements
3. Based on these figures, the electricity that must be import or export is evaluated

Once again, by looking at an example this should become clear. Let's take the values from hour 887 in Table 12. At the beginning of this hour there was a demand of 442 MW and a wind production of 1200 MW. Therefore, by following the steps outlined above, EnergyPLAN did the following:

1. The storage capacity from the hour before was 4351 MWh, while the total capacity was 5000 MWh. Therefore, the total capacity available for the next hour was 649 MWh, which equates to a pump demand of 812 MW (i.e. 649/0.8). Hence there is only room for 812 MW of excess electricity production in the storage during this hour.
2. As the total production during this hour is now 1200 MW of wind, there is now grid stabilising power operating. The regulation used states that 30% of all production must be grid stabilising. However, if the turbine starts producing power, it too will be adding to the production and hence the amount of grid stabilisation required will increase. For example, if the turbine provides 30% of the wind production, which is 360 MW (i.e. 0.3*1200), then the total production is now 1560 MW, but 360/1560 is only 23%, which is less than 30%. Therefore, the total power that must come from the turbine must account for its own production also and is calculated from (see section 8.3 of the EnergyPLAN user manual for full details on grid stabilisation calculations):

   Turbine = 0.3*(Wind+Turbine) = 0.3*(1200+Turbine) => 0.7Turbine = 360 => Turbine = 514 MW

   As the turbine needs to produce 514 MW, it means that 643 MWh (514/0.8) must be removed from the storage facility, so the balance in the storage facility during this hour is 4351 + 649 – 643 = **4357** MWh.
3. Now that EnergyPLAN has evaluated that the maximum electricity it can store is 812 MW and the total electricity it needs for stabilisation is 514 MW, it can equate how much electricity is left for export, which is 1200 + 514 - 812 - 442 = 460 MW. Note that this has a tolerance of ±1 MW as the decimal place may be greater or less than 0.5.

An important issue to notice here is the value recorded for the storage facility at the end of the hour. Even though the value recorded was 4357 MWh, the storage capacity was full during the calculations i.e. after the pump demand was added: 4351 + 649 = 5000 MWh. Therefore, when analysing the results for a double penstock, the 'Maximum Storage' for the PHES facility may not register as the storage capacity, even though it has been full during the analysis.

For clarity purposes, let's look at another example: hour 5 from Table 10:

1. There is 1000 MW and 5000 MWh of pump and storage capacity available respectively.
2. There is 750 MW of wind and 0 MW of grid stabilising power. Therefore, the turbine capacity required is: Turbine = 0.3*(Wind+Turbine) = 321 MW.
3. Now that the total production is 1071 MW (750+321), but the demand is only 331 MW, 740 MW is sent to the storage as there is sufficient pump and storage capacity available. Therefore, the balance for the storage is 592 MWh (740*0.8) in and 401 MWh out (321/0.8), which means the value at the end of the hour is 40 + 592 - 401 = 231 MWh.
4. Finally, all the excess power was sent to the storage and all of the grid stabilising power was provided by the turbine, so no export or import occurred.

Finally, the single penstock is evaluated in the same way, except if excess power and grid stabilisation must be provided at the same time, the excess power is prioritised (i.e. pump operates) and the power-plants (PP) provide the grid stabilisation (i.e. as the turbine cannot operate when the pump is operating).

Table 12
Calculating the hour pump and turbine demand for a double penstock PHES

hour	elec. demand	wind power	pp	pump	turbine	storage	stab. load	import	CEEP	EEEP
885	500	1230	0	1000	527	4220	100	0	257	0
886	472	1212	0	975	519	4351	100	0	284	0
887	**442**	**1200**	**0**	**812**	**514**	**4357**	**100**	**0**	**461**	**0**
888	403	1008	0	804	432	4460	100	0	233	0
889	383	982	0	675	421	4474	100	0	345	0
890	363	1116	0	658	478	4402	100	0	574	0

4.7 Description of 'stab.-load' from EnergyPLAN results window

As displayed in Figure 20, there is a number of grid stabilisation regulations that can be specified under the Regulation tab. This includes that "Minimum grid stabilisation production share" (MGSPS), which specifies the percentage of production that must be from grid stabilising units (i.e. power-plants, hydro, etc). It is important to remember that this is a percentage of total production and not total demand, which is outlined in detail in the user manual in section 8.3.

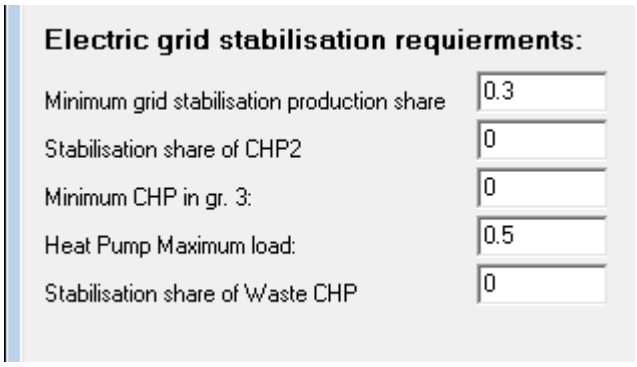
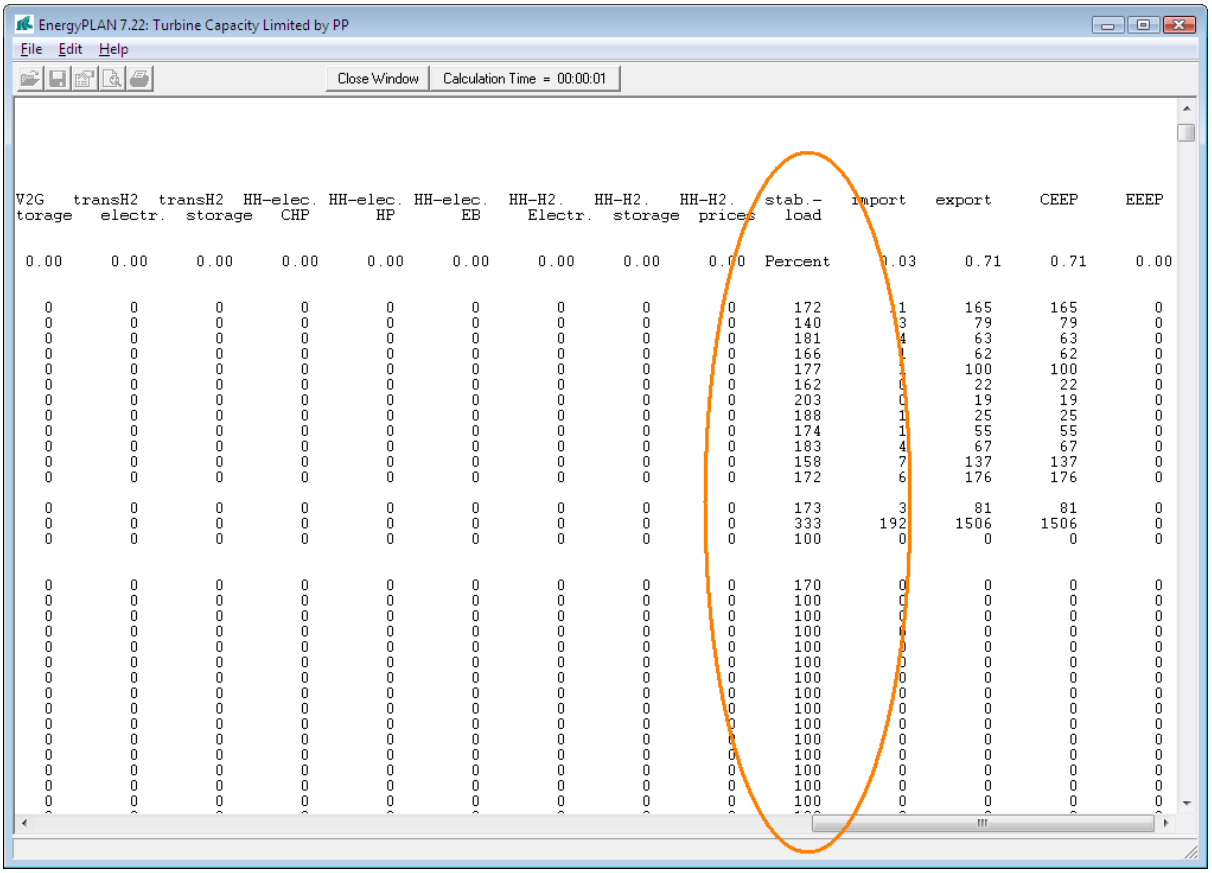


Figure 20: Grid stabilisation criteria in the EnergyPLAN model

To measure if the system provided the MGSPS during each hour of the simulation, EnergyPLAN calculates the "stab.-load", as shown in Figure 21. This illustrates the percentage of the MGSPS that was satisfied during each hour. This section illustrates how the stab.-load is calculated.



V2G storage	transH2 electr.	transH2 storage	HH-elec. CHP	HH-elec. HP	HH-elec. EB	HH-H2. Electr.	HH-H2. storage	HH-H2. prices	stab.-load	import	export	CEEP	EEEP
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Percent	0.03	0.71	0.71	0.00
0	0	0	0	0	0	0	0	0	172	1	165	165	0
0	0	0	0	0	0	0	0	0	140	3	79	79	0
0	0	0	0	0	0	0	0	0	181	4	63	63	0
0	0	0	0	0	0	0	0	0	166	1	62	62	0
0	0	0	0	0	0	0	0	0	177	1	100	100	0
0	0	0	0	0	0	0	0	0	162	0	22	22	0
0	0	0	0	0	0	0	0	0	203	0	19	19	0
0	0	0	0	0	0	0	0	0	188	1	25	25	0
0	0	0	0	0	0	0	0	0	174	1	55	55	0
0	0	0	0	0	0	0	0	0	183	4	67	67	0
0	0	0	0	0	0	0	0	0	158	7	137	137	0
0	0	0	0	0	0	0	0	0	172	6	176	176	0
0	0	0	0	0	0	0	0	0	173	3	81	81	0
0	0	0	0	0	0	0	0	0	333	192	1506	1506	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	170	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0
0	0	0	0	0	0	0	0	0	100	0	0	0	0

Figure 21: Stab. Load results displayed in EnergyPLAN

In section 8.3 of the EnergyPLAN user manual, it states that the percentage of electricity production from grid stabilising units, GridStab, is found from:

$$GridStab = \frac{e_{Stab}}{d_{Stab}} * 100 \quad (4)$$

Where e_{Stab} is the total electricity production from grid stabilising units and d_{Stab} is the minimum grid stabilisation production share that was specified in EnergyPLAN (as shown in Figure 20). Using this value the stab.-load is then calculated from:

$$stab.-load = \frac{GridStab}{MGSPS} \quad (5)$$

To make this clear, let's look at hour 1 for a double penstock-system in Table 10. In Table 10, all of the production units are highlighted in red and all of the demand units are highlighted in green. Therefore, for hour 1 the total production is 397 MW, with 203 MW produced by the turbine and 194 MW produced by wind power. However, only the PHES turbine provides grid stabilising power and as a result, the GridStab value for this hour is (203/397)*100 = 51%. However, the MGSPS required is 30%, see Table 11 and Figure 20. Therefore, the stab.-load is 51%/30% = 170%, as displayed in Table 10.

Let's calculate the stab.-load for hour 3 of the double penstock-system in Table 10 also. It is clear from Table 10 that during this hour the total production is 572 MW, with 400 MW from wind power, 38 MW from power-plants, and 134 MW from the PHES turbine. As specified in the EnergyPLAN user manual, both power-plants and the PHES turbine can provide grid stabilising power. Therefore, the total grid stabilising power production

for hour 3 is 172 MW (38+134). This means that GridStab = (172/572)*100 = 30% and stab.load=30%/30% = 100%.

Note: There are a number of areas in EnergyPLAN that I still do not understand, primarily because I have not needed to use these technologies or calculations to date. If anyone would like to add some information to any of these areas, please contact me at david.connolly@ul.ie.

5 Verifying Reference Model Data

Once all the data has been inputted into EnergyPLAN, the final step is to verify that the model created is operating the same as the energy-system that you are trying to simulate.

The first step is to ensure that all the capacities and distributions are correct, including interconnection capacity that is placed under the Regulation tab. Afterwards, the energy outputs from the model must be compared with those of the actual energy-system. There are five guidelines listed below that may be useful for completing this task (see Figure 22 also):

1. Check that the electricity demand is correct (including demand, heating, cooling and interconnection)
2. Ensure the consumption is also correct at point 2
3. Check that the production other than the power plants are producing the required amount of energy
4. Are the power plants generating the correct amount of energy for each fuel type? If steps 3 and 4 are correct, but the power plants are not generating the correct amount of energy, then the power plant efficiency under the Input -> DistrictHeating tab needs to be adjusted.
5. Is the total amount of fuel being used within the energy-system correct?

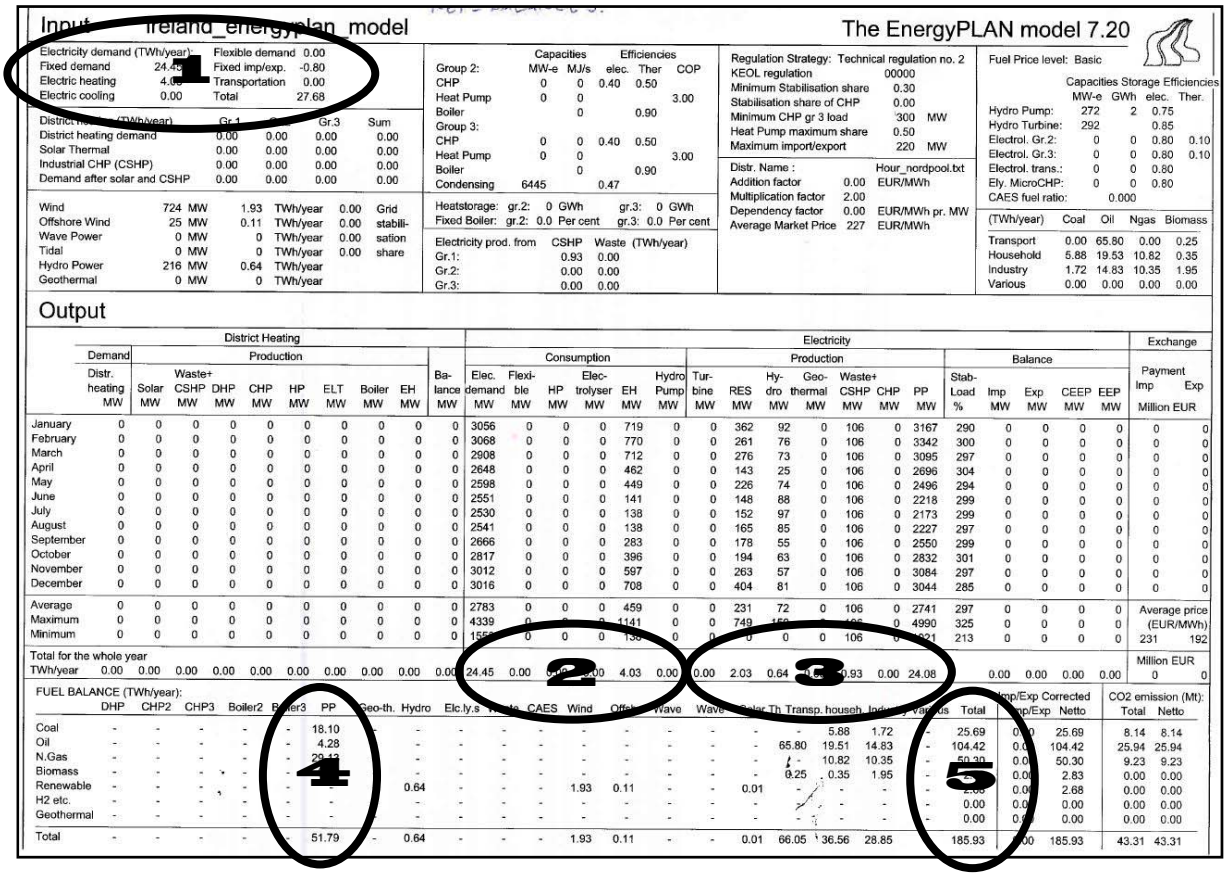


Figure 22: Verifying the EnergyPLAN model is functioning accurately

6 Common Error Screens

These are some of the common error screens that I saw during the time that I used EnergyPLAN, with a brief explanation of their cause.

6.1 Wrong Number of Data Points

If you do not have 8784 data points within a distribution in your model, you will get an error that says ***" is not a valid floating point value*** as shown in Figure 23. You need to have 8784 data points so that there is a data point for each hour of the year (366 hours * 24 days).

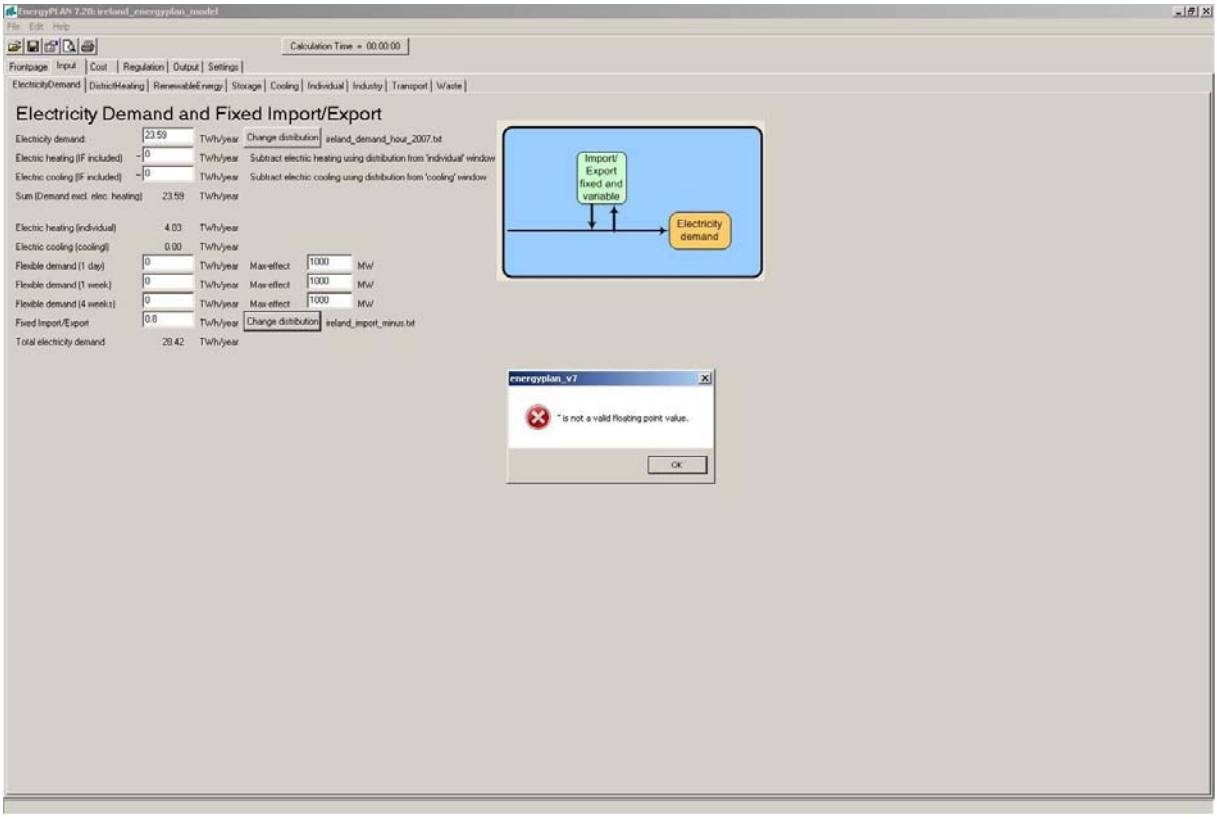


Figure 23: Error that occurs with the wrong number of data points in a distribution

6.2 Distribution File Location

If the distribution file that you have used is not located in the Distributions folder that you downloaded with the EnergyPLAN model, you will receive an error that says **File not found: location\distribution_name.txt** as shown in Figure 24.

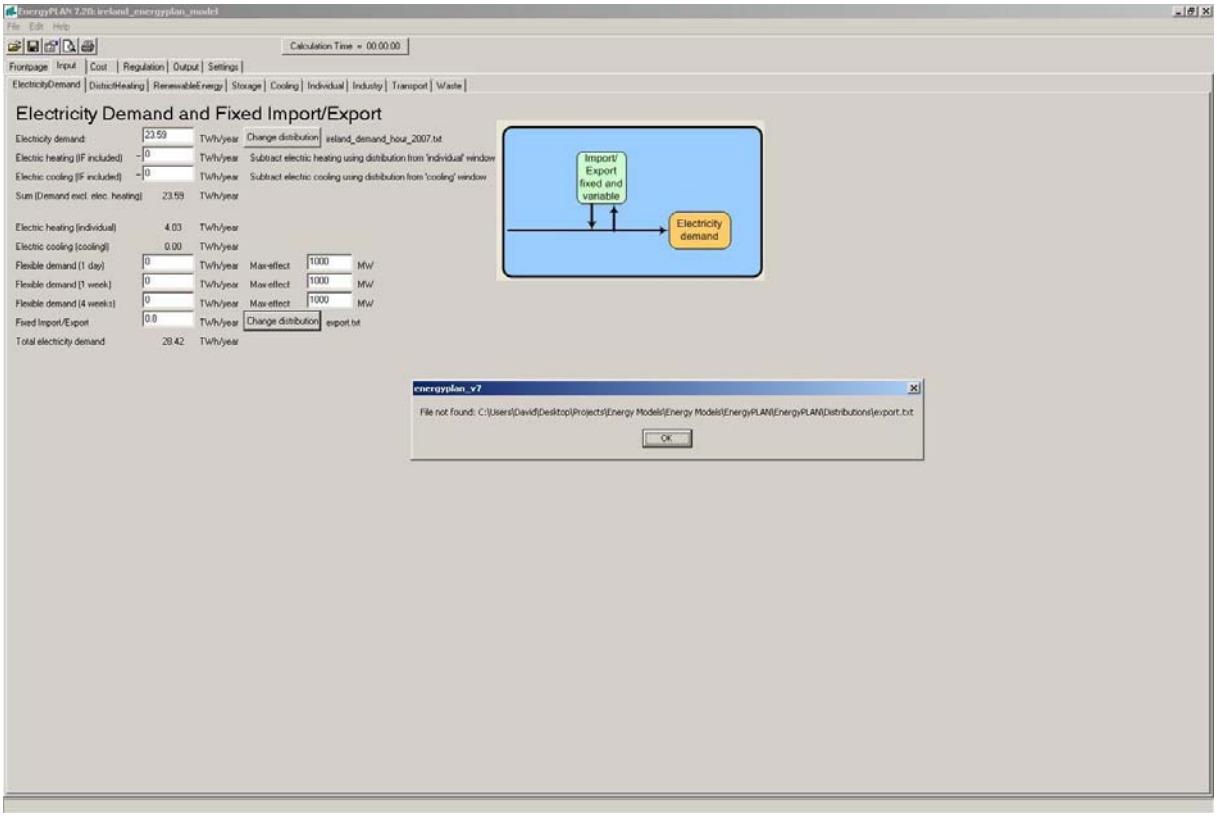


Figure 24: Error that occurs when the distribution is placed in the wrong folder

6.3 Warnings

A WARNING sign will be activated on the results screen (see Figure 25) and on the results print-out (see Figure 26) if any of the three following incident happens:

1. Excess electricity production.
2. Grid stabilisation is below requested level.
3. The specified electricity demand (e.g. for BEV) cannot be met by the capacity of power plants in combination with import on the transmission line capacity.

For example, Figure 25 below illustrates the warning displayed on the results screen of the EnergyPLAN tool when excess electricity production occurs, while Figure 26 illustrates the same warning on the results print-out of EnergyPLAN.

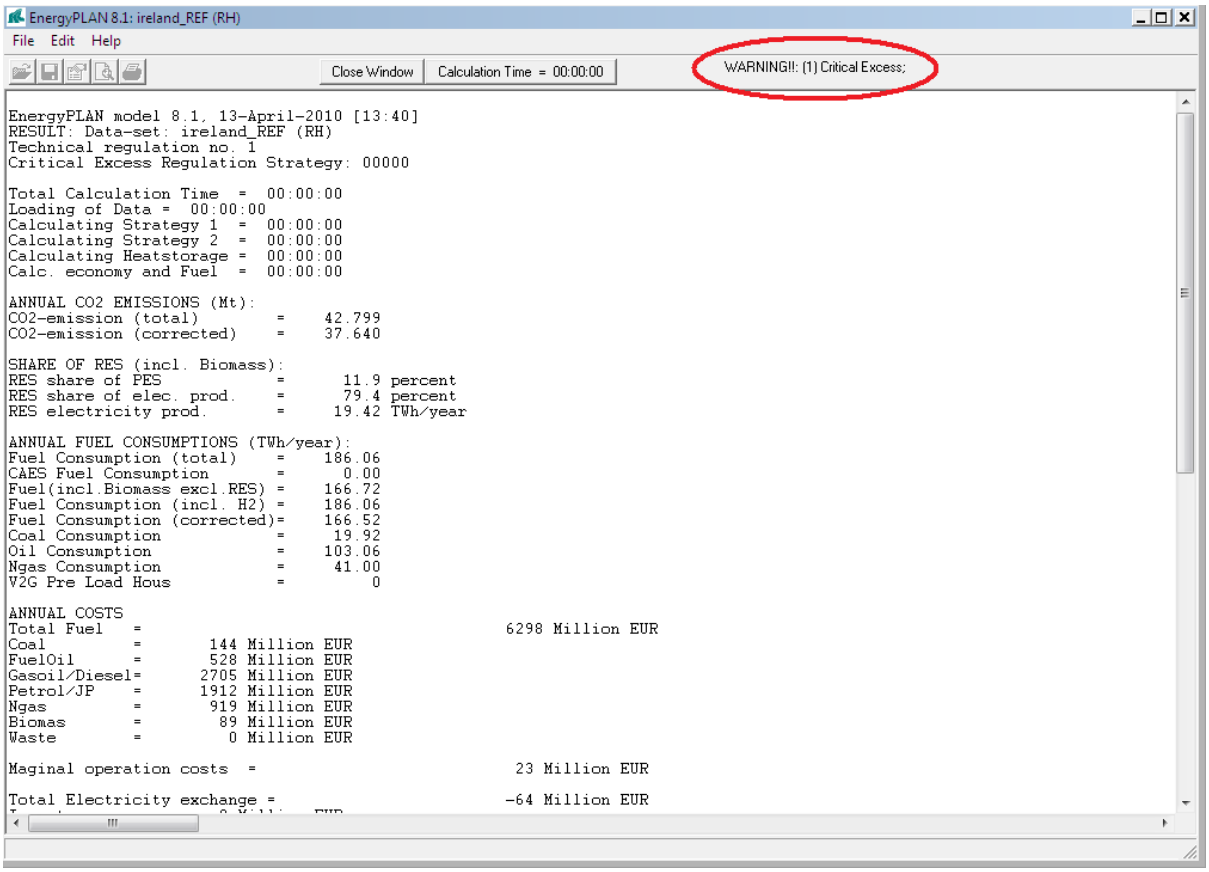
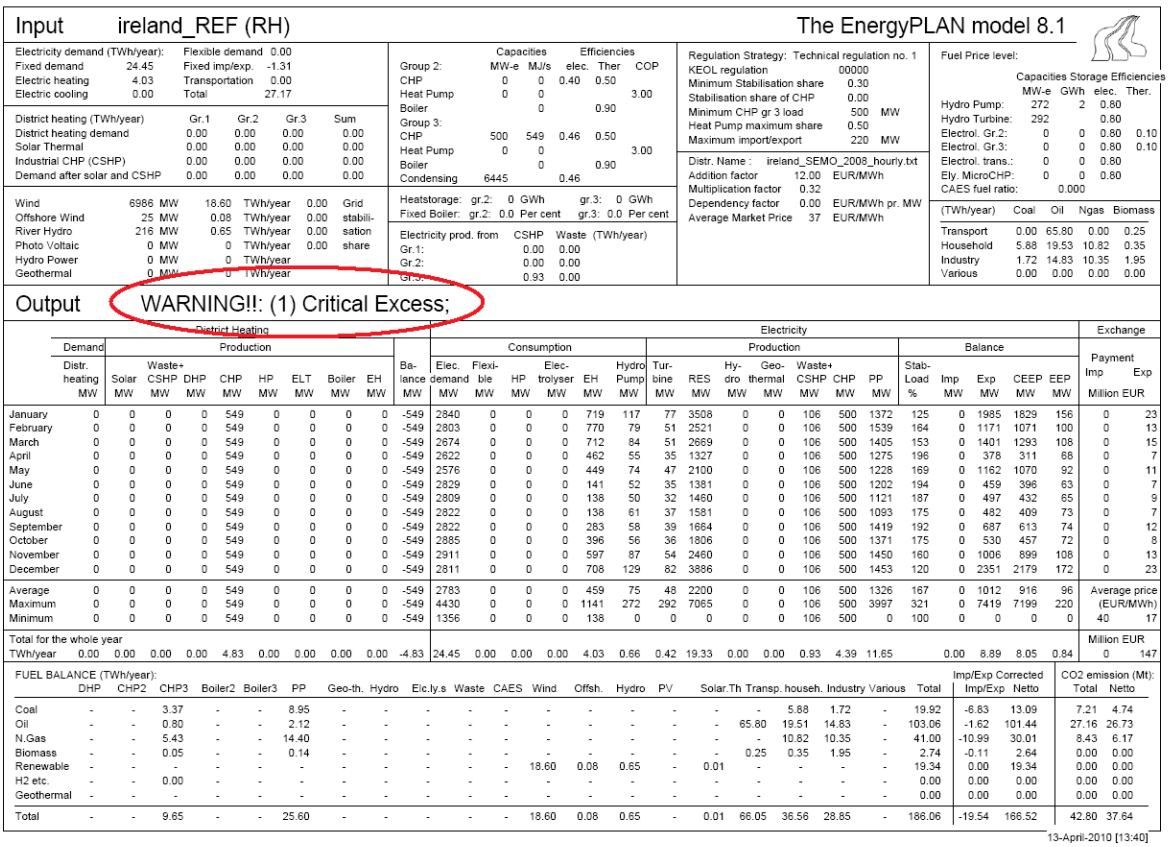

EnergyPLAN 8.1: ireland_REF (RH)
File Edit Help
Close Window
Calculation Time = 00:00:00
WARNING!!: (1) Critical Excess;
EnergyPLAN model 8.1, 13-April-2010 [13:40]
RESULT: Data-set: ireland_REF (RH)
Technical regulation no. 1
Critical Excess Regulation Strategy: 00000
Total Calculation Time = 00:00:00
Loading of Data = 00:00:00
Calculating Strategy 1 = 00:00:00
Calculating Strategy 2 = 00:00:00
Calculating Heatstorage = 00:00:00
Calc. economy and Fuel = 00:00:00
ANNUAL CO2 EMISSIONS (Mt):
CO2-emission (total) = 42.799
CO2-emission (corrected) = 37.640
SHARE OF RES (incl. Biomass):
RES share of PES = 11.9 percent
RES share of elec. prod. = 79.4 percent
RES electricity prod. = 19.42 TWh/year
ANNUAL FUEL CONSUMPTIONS (TWh/year):
Fuel Consumption (total) = 186.06
CAES Fuel Consumption = 0.00
Fuel(incl.Biomass excl.RES) = 166.72
Fuel Consumption (incl. H2) = 186.06
Fuel Consumption (corrected)= 166.52
Coal Consumption = 19.92
Oil Consumption = 103.06
Ngas Consumption = 41.00
V2G Pre Load Hous = 0
ANNUAL COSTS
Total Fuel = 6298 Million EUR
Coal = 144 Million EUR
FuelOil = 528 Million EUR
Gasoil/Diesel= 2705 Million EUR
Petrol/JP = 1912 Million EUR
Ngas = 919 Million EUR
Biomas = 89 Million EUR
Waste = 0 Million EUR
Maginal operation costs = 23 Million EUR
Total Electricity exchange = -64 Million EUR

Figure 25: Sample of the WARNING for excess electricity production on the results screen of EnergyPLAN



Input ireland_REF (RH) The EnergyPLAN model 8.1

Electricity demand (TWh/year): Flexible demand 0.00
Fixed demand 24.45 Fixed imp/exp. -1.31
Electric heating 4.03 Transportation 0.00
Electric cooling 0.00 Total 27.17

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.00	0.00	0.00	0.00
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.00	0.00	0.00	0.00

Wind	6986	MW	18.60	TWh/year	0.00 Grid
Offshore Wind	25	MW	0.08	TWh/year	0.00 stabili-
River Hydro	216	MW	0.65	TWh/year	0.00 sation
Photo Voltaic	0	MW	0	TWh/year	0.00 share
Hydro Power	0	MW	0	TWh/year	
Geothermal	0	MW	0	TWh/year	

	Capacities MW-e	MJ/s	Efficiencies elec.	Ther	COP
Group 2:					
CHP	0	0	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	500	549	0.46	0.50	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Condensing	6445		0.46		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.00	0.00
Gr.2:	0.00	0.00
Gr.3:	0.93	0.00

Regulation Strategy: Technical regulation no. 1
KEOL regulation 00000
Minimum Stabilisation share 0.30
Stabilisation share of CHP 0.00
Minimum CHP gr 3 load 500 MW
Heat Pump maximum share 0.50
Maximum import/export 220 MW

Distr. Name : ireland_SEMO_2008_hourly.txt
Addition factor 12.00 EUR/MWh
Multiplication factor 0.32
Dependency factor 0.00 EUR/MWh pr. MW
Average Market Price 37 EUR/MWh

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficiencies elec.	Ther.
Hydro Pump:	272	2	0.80	
Hydro Turbine:	292		0.80	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	
CAES fuel ratio:		0.000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	65.80	0.00	0.25
Household	5.88	19.53	10.82	0.35
Industry	1.72	14.83	10.35	1.95
Various	0.00	0.00	0.00	0.00

Output WARNING!!: (1) Critical Excess;

	District Heating Demand	Production								Balance	Consumption						Electricity Production								Balance					Exchange Payment	
	Distr. heating MW	Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flexi-ble MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million EUR	Exp Million EUR
January	0	0	0	0	549	0	0	0	0	-549	2840	0	0	0	719	117	77	3508	0	0	106	500	1372	125	0	1985	1829	156	0	23
February	0	0	0	0	549	0	0	0	0	-549	2803	0	0	0	770	79	51	2521	0	0	106	500	1539	164	0	1171	1071	100	0	13
March	0	0	0	0	549	0	0	0	0	-549	2674	0	0	0	712	84	51	2669	0	0	106	500	1405	153	0	1401	1293	108	0	15
April	0	0	0	0	549	0	0	0	0	-549	2622	0	0	0	462	55	35	1327	0	0	106	500	1275	196	0	378	311	68	0	7
May	0	0	0	0	549	0	0	0	0	-549	2576	0	0	0	449	74	47	2100	0	0	106	500	1228	169	0	1162	1070	92	0	11
June	0	0	0	0	549	0	0	0	0	-549	2829	0	0	0	141	52	35	1381	0	0	106	500	1202	194	0	459	396	63	0	7
July	0	0	0	0	549	0	0	0	0	-549	2809	0	0	0	138	50	32	1460	0	0	106	500	1121	187	0	497	432	65	0	9
August	0	0	0	0	549	0	0	0	0	-549	2822	0	0	0	138	61	37	1581	0	0	106	500	1093	175	0	482	409	73	0	7
September	0	0	0	0	549	0	0	0	0	-549	2822	0	0	0	283	58	39	1664	0	0	106	500	1419	192	0	687	613	74	0	12
October	0	0	0	0	549	0	0	0	0	-549	2885	0	0	0	396	56	36	1806	0	0	106	500	1371	175	0	530	457	72	0	8
November	0	0	0	0	549	0	0	0	0	-549	2911	0	0	0	597	87	54	2460	0	0	106	500	1450	160	0	1006	899	108	0	13
December	0	0	0	0	549	0	0	0	0	-549	2811	0	0	0	708	129	82	3886	0	0	106	500	1453	120	0	2351	2179	172	0	23
Average	0	0	0	0	549	0	0	0	0	-549	2783	0	0	0	459	75	48	2200	0	0	106	500	1326	167	0	1012	916	96	Average price (EUR/MWh)	
Maximum	0	0	0	0	549	0	0	0	0	-549	4430	0	0	0	1141	272	292	7065	0	0	106	500	3997	321	0	7419	7199	220		
Minimum	0	0	0	0	549	0	0	0	0	-549	1356	0	0	0	138	0	0	0	0	0	106	500	0	100	0	0	0	0	40	17
Total for the whole year TWh/year	0.00	0.00	0.00	0.00	4.83	0.00	0.00	0.00	0.00	-4.83	24.45	0.00	0.00	0.00	4.03	0.66	0.42	19.33	0.00	0.00	0.93	4.39	11.65		0.00	8.89	8.05	0.84	Million EUR 0	147

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo-th.	Hydro	Elc.ly.s	Waste	CAES	Wind	Offsh.	Hydro	PV	Solar.Th	Transp.	househ.	Industry	Various	Total	Imp/Exp Corrected Imp/Exp	Imp/Exp Corrected Netto	CO2 emission (Mt): Total	CO2 emission (Mt): Netto
Coal	-	-	3.37	-	-	8.95	-	-	-	-	-	-	-	-	-	-	-	5.88	1.72	-	19.92	-6.83	13.09	7.21	4.74
Oil	-	-	0.80	-	-	2.12	-	-	-	-	-	-	-	-	-	-	65.80	19.51	14.83	-	103.06	-1.62	101.44	27.16	26.73
N.Gas	-	-	5.43	-	-	14.40	-	-	-	-	-	-	-	-	-	-	-	10.82	10.35	-	41.00	-10.99	30.01	8.43	6.17
Biomass	-	-	0.05	-	-	0.14	-	-	-	-	-	-	-	-	-	-	0.25	0.35	1.95	-	2.74	-0.11	2.64	0.00	0.00
Renewable	-	-	-	-	-	-	-	-	-	-	-	18.60	0.08	0.65	-	0.01	-	-	-	-	19.34	0.00	19.34	0.00	0.00
H2 etc.	-	-	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Geothermal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	-	-	9.65	-	-	25.60	-	-	-	-	-	18.60	0.08	0.65	-	0.01	66.05	36.56	28.85	-	186.06	-19.54	166.52	42.80	37.64

13-April-2010 [13:40]

Figure 26: Sample of the WARNING for excess electricity production on the results print-out of EnergyPLAN

7 Conclusions

The EnergyPLAN model is extremely useful because it is simple. However, this simplicity creates a responsibility on the user to ensure that the data inputted is as accurate and applicable as possible. The time required to build the reference model is cumbersome as there is a lot of false-paths along the way. However, the wave of possibilities that present themselves upon completion of the reference model, ensure that the time spent searching for data becomes a worthy experience.

Once the reference model is completed, it is possible to build and analyse energy-systems with endless quantities of renewable, conventional, storage and transport technologies, in a relatively short period of time. Hopefully upon completion of my study, I will be able to expand the benefits of EnergyPLAN even further.

Finally, the level of detail discussed in this report is not necessary for every study completed using EnergyPLAN, especially in relation to the distributions used. Therefore, before spending a large period of time gathering data, ensure that the data is required for the accuracy of the results.

8 Appendix

8.1 Ireland's Energy-Balance 2007

Ireland's Provisional Energy Balance 2007 (TWh)

2007 Units = TWh	Coal	Bituminous Coal	Anthracite + Manufactured Ovoids	Coke	Lignite	Peat	Milled Peat	Sod Peat	Briquettes	Oil	Crude	Refinery Gas	Gasoline	Kerosene	Jet Kerosene	Fueloil	LPG	Gasoil / Diesel /DERV	Petroleum Coke	Naphta	Bitumen	White Spirit	Lubricants	Natural Gas	Renewables	Hydro	Wind	Biomass	Landfill Gas	Biogas	Liquid Biofuel	Solar	Geothermal	Electricity	Heat	TOTAL
Indigenous Production	0.000	0.000	0.000	0.000	6.876	4.711	2.165	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.344	5.211	0.925	1.959	1.961	0.278	0.011	0.196	0.015	0.003	1.413	0.000	18.369
Imports	14.517	14.077	0.380	0.360	0.306	0.000	0.000	0.000	12.914	40.373	0.000	14.817	5.820	12.916	6.863	1.507	3.972	32.151	0.000	2.765	1.393	0.117	45.631	0.285	0.050	0.000	0.146	0.000	0.000	0.000	0.000	0.000	0.000	0.149	0.000	185.240
Exports	0.036	0.000	0.036	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.321	0.202	0.000	0.000	13.181	0.176	0.725	0.000	0.152	0.881	0.070	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.082	0.000	15.315
Mar. Bunkers	1.059	0.999	0.060	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.044	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.103
Stock Change	17.540	17.076	0.464	0.000	0.076	4.711	2.165	0.000	0.000	40.263	0.000	14.540	5.390	13.476	6.863	1.326	3.796	31.911	3.950	4.117	2.765	0.562	0.047	49.923	5.427	0.925	1.959	2.135	0.278	0.011	0.196	0.015	0.003	1.331	0.000	187.398
Primary Energy Supply (incl non-energy)	17.540	17.076	0.464	0.000	0.076	4.711	2.165	0.000	0.000	40.263	0.000	14.540	5.390	13.476	6.863	1.326	3.796	31.911	3.950	4.117	2.765	0.562	0.047	49.923	5.427	0.925	1.959	2.135	0.278	0.011	0.196	0.015	0.012	1.331	0.000	187.398
Primary Energy Requirement (excl non-energy)	13.071	13.071	0.000	0.000	0.076	4.711	2.165	0.000	0.000	40.263	0.000	14.540	5.390	13.476	6.863	1.326	3.796	31.911	3.950	4.117	2.765	0.562	0.047	49.923	5.427	0.925	1.959	2.135	0.278	0.111	0.196	0.015	0.012	1.331	0.000	187.398
Transformation Input	13.071	13.071	0.000	0.000	6.186	0.000	0.000	0.000	44.934	40.263	0.093	0.000	0.000	0.000	0.000	0.000	0.000	0.042	0.000	0.000	0.000	0.000	0.000	31.830	0.384	0.000	0.000	0.038	0.278	0.068	0.000	0.000	0.000	0.729	0.000	96.833
Public Thermal Power Plants	13.071	13.071	0.000	0.000	5.010	0.000	0.000	0.000	4.275	0.000	0.000	0.000	0.000	0.000	0.000	4.233	0.000	0.042	0.000	0.000	0.000	0.000	0.000	29.492	0.279	0.000	0.000	0.001	0.278	0.000	0.000	0.000	0.000	0.000	0.000	51.727
Combined Heat and Power Plants	0.000	0.000	0.000	0.000	0.082	0.000	0.000	0.000	0.096	0.000	0.093	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.338	0.105	0.000	0.000	0.037	0.000	0.068	0.000	0.000	0.000	0.546	0.000	3.021
Pumped Storage Consumption	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Briquetting Plants	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Oil Refineries & other energy sector	0.000	0.000	0.000	0.000	1.093	1.093	0.000	0.000	0.000	40.263	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.182	0.000	40.445
Transformation Output	0.000	0.000	0.000	0.000	1.100	0.000	0.000	0.000	39.049	0.000	0.000	1.085	6.108	2.459	0.000	14.222	0.448	14.490	0.000	0.117	0.000	0.000	0.000	0.132	0.000	0.000	0.000	0.013	0.102	0.017	0.000	0.000	0.000	2.758	0.000	65.786
Public Thermal Power Plants	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.102	0.000	0.000	0.000	0.102	0.000	0.000	0.000	0.000	0.000	23.330	0.000	23.432
Combined Heat and Power Plants - Electricity	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.000	0.000	0.000	0.013	0.000	0.017	0.000	0.000	0.000	1.826	0.000	1.856
Combined Heat and Power Plants - Heat	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pumped Storage Generation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Briquetting Plants	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Oil Refineries	0.000	0.000	0.000	0.000	1.100	0.000	0.000	0.000	39.049	0.000	0.000	1.085	6.108	2.459	0.000	14.222	0.448	14.490	0.000	0.117	0.000	0.000	0.000	0.132	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.758	0.000	65.786
Exchanges and transfers	0.194	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-2.758	-0.467	-1.959	-0.013	-0.102	-0.017	0.000	0.000	0.000	2.758	0.000	0.000
Electricity	-0.124	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-2.758	-0.467	-1.959	-0.013	-0.102	-0.017	0.000	0.000	0.000	2.758	0.000	0.000
Heat	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other	0.194	-0.124	0.317	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Own Use and Distribution Losses	0.300	0.000	0.300	0.000	0.176	0.000	0.000	0.000	1.431	0.000	0.902	0.000	0.000	0.000	0.000	0.345	0.045	0.000	0.000	0.000	0.000	0.000	0.000	0.865	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.666
Available Final Energy Consumption	4.663	3.881	0.706	0.000	0.076	2.897	2.163	0.992	101.493	0.000	0.000	20.566	16.072	11.264	4.461	1.802	46.217	3.736	0.000	2.765	0.562	0.047	17.427	2.417	0.000	0.000	2.097	0.000	0.000	0.044	0.250	0.015	0.012	26.196	0.000	155.096
Non-Energy Consumption	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.374	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.765	0.562	0.047	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.374
Final non-Energy Consumption (Feedstocks)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.374	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.765	0.562	0.047	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.374
Total Final Energy Consumption	4.354	3.568	0.769	0.000	0.076	3.159	2.167	0.992	100.064	0.000	0.000	22.325	16.420	12.134	4.295	1.853	45.188	3.637	0.012	0.000	0.000	0.000	18.424	2.476	0.000	0.000	2.155	0.000	0.044	0.249	0.015	0.012	25.867	0.000	154.343
Industry*	1.630	1.630	0.000	0.000	0.003	0.000	0.000	0.003	11.799	0.000	0.000	0.000	1.438	0.000	0.000	4.180	0.813	2.076	3.280	0.012	0.000	0.000	7.616	1.769	0.000	0.000	1.752	0.000	0.017	0.000	0.000	0.000	8.478	0.000	31.295
Non-Energy Mining	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.493	0.000	0.000	0.000	0.015	0.000	0.000	0.060	0.001	0.416	0.000	0.000	0.000	0.000	0.420	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.668	0.000	1.582
Food, beverages and tobacco	0.160	0.160	0.000	0.000	0.000	0.000	0.000	0.000	1.457	0.000	0.000	0.000	0.188	0.000	0.000	0.731	0.051	0.488	0.000	0.000	0.000	0.000	2.028	0.684	0.000	0.000	0.667	0.000	0.000	0.017	0.000	0.000	1.987	0.000	6.316
Textiles and textile products	0.075	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.119	0.000	0.000	0.000	0.009	0.000	0.000	0.036	0.018	0.056	0.000	0.000	0.000	0.000	0.017	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.096	0.000	0.308
Wood and wood products	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.146	0.000	0.000	0.000	0.018	0.000	0.000	0.070	0.000	0.058	0.000	0.000	0.000	0.000	0.046	1.085	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.348	0.000	1.626
Pulp, paper, publishing and printing	0.004	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.088	0.000	0.000	0.000	0.009	0.000	0.000	0.033	0.009	0.037	0.000	0.000	0.000	0.000	0.262	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.369	0.000	0.723
Chemicals & man-made fibres	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.563	0.000	0.000	0.000	0.076	0.000	0.000	0.294	0.015	0.179	0.000	0.000	0.000	0.000	1.429	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.189	0.000	3.182
Rubber and plastic products	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.070	0.000	0.000	0.000	0.002	0.000	0.000	0.006	0.000	0.054	0.000	0.000	0.000	0.000	0.113	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.373	0.000	0.556
Other non-metallic mineral products	1.391	1.391	0.000	0.000	0.000	0.000	0.000	0.000	3.913	0.000	0.000	0.000	0.032	0.000	0.000	0.126	0.037	0.439	3.280	0.000	0.000	0.000	0.635	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.635	0.000	6.574
Basic metals and fabricated metal products	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.763	0.000	0.000	0.000	1.037	0.000	0.000	2.619	0.090	0.078	0.000	0.000	0.000	0.000	2.058	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.869	0.000	6.690
Machinery and equipment n.e.c.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.096	0.000	0.000	0.000	0.008	0.000	0.000	0.029	0.024	0.035	0.000	0.000	0.000	0.000	0.154	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.200	0.000	0.450
Electrical and optical equipment	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.849	0.000	0.000	0.000	0.020	0.000	0.000	0.078	0.612	0.139	0.000	0.000	0.000	0.000	0.326	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.330	0.000	2.505
Transport equipment manufacture	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.031	0.000	0.000	0.000	0.002	0.000	0.000	0.006	0.001	0.022	0.000	0.000	0.000	0.000	0.098	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.107	0.000	0.236
Other manufacturing	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.003	0.211	0.000	0.000	0.000	0.023	0.000	0.000	0.090	0.011	0.074	0.000	0.012	0.000	0.000	0.029	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.307	0.000	0.549
Transport	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	65.812	0.000	0.000	22.325	0.000	12.134	0.000	0.000	0.012	31.341	0.000	0.000	0.000	0.000	0.000	0.249	0.000	0.000	0.000	0.000	0.000	0.000	0.249	0.000	0.000	0.052	0.000	66.113
Road Freight	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	13.798	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	13.798	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	13.798
Road Private Car	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	25.141	0.000	0.000	18.840	0.000	0.000	0.000	0.000	0.012	6.290	0.000	0.000	0.000	0.000	0.000	0.249	0.000	0.000	0.000	0.000	0.000	0.000	0.249	0.000	0.000	0.000	25.391
Public Passenger Services	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.088	0.000	0.000	0.526	0.000	0.000	0.000	0.000	0.000	1.562	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.088
Rail	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.500
Domestic Aviation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.625	0.000	0.000	0.019	0.000	0.000	0.000	0.607	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.625
International Aviation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	11.527	0.000	0.000	0.000	0.000	11.527	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	11.527
Fuel Tourism	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.364	0.000	0.000	2.121	0.000	0.000	0.000	0.000	0.000	5.243	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	7.364
Unspecified	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.769	0.000	0.000	0.820	0.000	0.000	0.000	0.000	0.000	3.948	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.769
Residential	2.420	1.653	0.699	0.000	0.048	3.155	0.000	2.167	13.113	0.000	0.000	0.000	9.182	0.000	0.000	0.000	0.897	2.676	0.358	0.000	0.000	0.000	6.896	0.282	0.000	0.000	0.262	0.000	0.000	0.000	0.015	0.005	8.064	0.000	33.930
Commercial/Public Services	0.303	0.285	0.010	0.000	0.008	0.000	0.000	0.000	6.405	0.000	0.000	0.000	0.000	0.115	0.132	6.159	0.095	0.000	0.000	0.000	0.000	0.000	3.913	0.095	0.000	0.000	0.061	0.000	0.000	0.027	0.000	0.006	8.711	0.000	19.427
Commercial Services	0.303	0.285	0.010	0.000	0.008	0.000	0.000	0.000	4.178	0.000	0.000	0.000	0.000	0.011	0.098	4.069	0.000	0.000	0.000	0.000	0.000	0.000	1.715	0.095	0.000	0.000	0.061	0.000	0.000	0.027	0.000	0.006	6.245	0.000	12.536
Public Services	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.227	0.000	0.000	0.000	0.000	0.103	0.034	2.090	0.000	0.000	0.000	0.000	0.000	0.000	2.198	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.466	0.000	6.892
Agricultural	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.936	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	2.936	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.561	0.000	3.577
Statistical Difference	0.310	0.313	-0.003	0.000	-0.262	-0.258	-0.004	0.000	-1.945	0.000	0.000	-1.759	-0.348	-0.870	0.166	-0.051	1.030	0.099	-0.012	0.000	0.000	0.000	-0.397	-0.058	0.000	0.000	-0.059	0.000	0.000	0.000	0.001	0.000	0.331	0.000	-2.621

* Industry sub-sectoral breakdown is based on the CIP 2004

Last Updated 24 Sep 2008

Key

2007 Provisional

9 References

[1] Lund H. EnergyPLAN: Advanced Energy System Analysis Computer Model, http://energy.plan.aau.dk/; 2009.

[2] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied Energy 2009;Article in Review.

[3] The Danish Society of Engineers. The Danish Society of Engineers' Energy Plan 2030. Available at. The Danish Society of Engineers, http://ida.dk/sites/climate/introduction/Documents/Energyplan2030.pdf; 2006.

[4] Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems--The case of Denmark in years 2030 and 2050. Energy 2009;34(5):524-531.

[5] Blarke MB, Lund H. The effectiveness of storage and relocation options in renewable energy systems. Renewable Energy 2008;33(7):1499-1507.

[6] Lund H. Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply. Renewable Energy 2006;31(4):503-515.

[7] Lund H. Large-scale integration of wind power into different energy systems. Energy 2005;30(13):2402-2412.

[8] SEI. Sustainable Energy Ireland, http://www.sei.ie/; 2009.

[9] International Energy Agency. Energy Balances of OECD Countries. Available at. International Energy Agency, http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=2033; 2008.

[10] International Energy Agency. Energy Balances of Non-OECD Countries. Available at. International Energy Agency, http://www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1078; 2008.

[11] Meteotest. METEONORM. Available at. Meteotest, http://www.meteonorm.com/pages/en/meteonorm.php; 2009.

[12] UCTE. We are UCTE. Available at. UCTE, http://www.ucte.org/aboutus/; 2009.

[13] UCTE. Data Portal. Available at. UCTE, http://www.ucte.org/resources/dataportal/; 2009.

[14] Howley M, Ó'Gallachóir B, Dennehy E. Energy in Ireland 1990 - 2007. Available at. Sustainable Energy Ireland, http://www.sei.ie/Publications/Statistics_Publications/EPSSU_Publications/; 2008.

[15] Lund H, Aalborg University. EnergyPLAN: Advanced Energy Systems Analysis Computer Model. Available at. Aalborg University, http://energy.plan.aau.dk/manual.php; 2008.

[16] Sustainable Energy Ireland. Wind Speed Mapping. Available at. Sustainable Energy Ireland, http://esb2.net.weblink.ie/SEI/MapPage.asp; 2003.

[17] Marine Institute. Irish Marine Weather Buoy Network. Available at. Marine Institute, http://www.marine.ie/home/publicationsdata/data/buoys/; 2009.

[18] Vestas. V90 - 3.0 MW. Available at. Vestas, http://www.vestas.com/en/wind-power-solutions/wind-turbines/3.0-mw.aspx; 2007.

[19] Hannevig D. Oriel Windfarm Limited: Grid Connection Presentation. Available at. EirGrid, http://www.eirgrid.com/media/(7)%20Offshore%20Wind%20-%20Dan%20Hannevig%20-%20Sure%20Engineering.pdf; 2007.

[20] EirGrid. Welcome to EirGrid, http://www.eirgrid.com/; 2009.

[21] SEMO. The Single Electricity Market Operator. Available at. SEMO, http://www.sem-o.com/; 2009.

[22] Task Committee on Pumped Storage of the Committee on Hydropower of the Energy Division of the American Society of Civil Engineers. Hydroelectric Pumped Storage Technology: International Experience. Available at. American Society of Civil Engineers, http://cedb.asce.org/cgi/WWWdisplay.cgi?9601277; 1996.

[23] Met Eireann. Degree Days. Available at. Met Eireann, http://www.met.ie/climate/degree-day.asp; 2009.

[24] The Chartered Institution of Building Services Engineers. Degree-days: theory and application. Available at. The Chartered Institution of Building Services Engineers, http://www.cibse.org/index.cfm?go=publications.view&item=356; 2006.

[25] Department for Business Enterprise & Regulatory Reform (United Kingdom). Energy Trends: September 2008. Available at. Department for Business Enterprise & Regulatory Reform (United Kingdom), http://www.berr.gov.uk/whatwedo/energy/statistics/publications/trends/index.html; 2008.

[26] Sustainable Energy Ireland. Dwellings Energy Assessment Procedure: Version 3. Available at. Sustainable Energy Ireland, http://www.sei.ie/Your_Building/BER/BER_Assessors/Technical/DEAP/; 2008.

[27] O'Leary F, Howley M, Ó'Gallachóir B, Sustainable Energy Ireland. Energy in the Residential Sector. Available at. Sustainable Energy Ireland, http://www.sei.ie/Publications/Statistics_Publications/EPSSU_Publications/; 2008.
[28] Department of Communications, Marine and Natural Resources. Bioenergy Action Plan for Ireland. Available at. Department of Communications, Marine and Natural Resources, http://www.dcenr.gov.ie/NR/rdonlyres/6D4AF07E-874D-4DB5-A2C5-63E10F9753EB/27345/BioenergyActionPlan.pdf; 2006.
[29] Sustainable Energy Ireland. Energy Balance 2007. Available at. Sustainable Energy Ireland, http://www.sei.ie/Publications/Statistics_Publications/2007_Energy_Balance/; 2008.
[30] PlanEnergi. The Danish Society of Engineers' Energy Plan 2030: Solar Distribution. Available at. PlanEnergi, http://www.planenergi.dk/; 2006.
[31] Central Statistics Office Ireland. Census 2006: Housing. Available at. Central Statistics Office Ireland, http://www.cso.ie/census/; 2007.
[32] Sustainable Energy Ireland. Tidal and Current Energy Resources in Ireland. Available at. Sustainable Energy Ireland, http://www.sei.ie/Publications/Renewables_Publications/ 2004.
[33] Electricity Supply Board (ESB) International. All-Island Grid-Study: Renewable Energy Resource Assessment (Workstream 1). Available at. Electricity Supply Board (ESB) International, http://www.dcenr.gov.ie/Energy/North-South+Co-operation+in+the+Energy+Sector/All+Island+Electricity+Grid+Study.htm; 2008.
[34] Whittaker T, Fraenkel PL, Bell A, Lugg L, The potential for the use of marine current energy in Northern Ireland. http://www.detini.gov.uk/cgi-bin/moreutil?utilid=41&site=99&util=2; 2003.
[35] Environmental Change Institute, University of Oxford. Variability of UK Marine Resources. Available at. Environmental Change Institute, University of Oxford, http://www.carbontrust.co.uk/NR/rdonlyres/EC293061-611D-4BC8-A75C-9F84138184D3/0/variability_uk_marine_energy_resources.pdf; 2005.
[36] Marine Institute. Marine Institute. Available at. Marine Institute, http://www.marine.ie/Home/; 2009.
[37] NDBC. National Data Buoy Center Stations. Available at. NDBC, http://www.ndbc.noaa.gov/to_station.shtml; 2007.
[38] International Energy Agency. World Energy Outlook 2008. Available at. International Energy Agency, http://www.worldenergyoutlook.org/2008.asp; 2008.
[39] Danish Energy Agency. Forudsætninger for samfundsøkonomiske analyser på energiområdet (Prerequisites for socio-economic analysis of energy). Available at. Danish Energy Agency (In Danish), http://www.ens.dk/sw80140.asp; 2009.
[40] Hamelinck C, van den Broek R, Rice B, Gilbert A, Ragwitz M, Toro F. Liquid Biofuels Strategy Study for Ireland. Available at. Sustainable Energy Ireland, http://www.sei.ie/uploadedfiles/InfoCentre/LiquidbiofuelFull.pdf; 2004.
[41] Sustainable Energy Ireland. A Study on Renewable Energy in the New Irish Electricity Market. Available at. Sustainable Energy Ireland, http://www.sei.ie/Publications/Renewables_Publications/; 2004.
[42] Danish Energy Agency, Ekraft System, Eltra. Technology Data for Electricity and Heat Generating Plants. Available at. Danish Energy Agency, Ekraft System, Eltra, http://www.energinet.dk/NR/rdonlyres/4F6480DC-207B-41CF-8E54-BF0BA82926D7/0/Teknologikatalog050311.pdf; 2005.
[43] Gonzalez A, Ó'Gallachóir B, McKeogh E, Lynch K. Study of Electricity Storage Technologies and Their Potential to Address Wind Energy Intermittency in Ireland. Available at. Sustainable Energy Ireland, http://www.sei.ie/Grants/Renewable_Energy_RD_D/Projects_funded_to_date/Wind/Study_of_Elec_Storage_Technologies_their_Potential_to_Address_Wind_Energy_Intermittency_in_Irl; 2004.
[44] Danish Energy Agency. Basisfremskrivning af Danmarks energiforbrug frem til 2025 (Forecast of the Danish Energy Supply until 2025). Available at. Danish Energy Agency (In Danish), http://www.ens.dk/graphics/Publikationer/Energipolitik/Basisfremskrivning_2007_170108/index.htm; 2008.
[45] Salmond N. Personal communication at the British Hydropower Association. Britain; 2008.
[46] CSO. Household Budget Survey 2004-2005: Final Results. Available at. CSO, http://www.cso.ie/releasespublications/pr_hseholds.htm; 2007.
[47] Lund H. A Green Energy Plan for Denmark. Environmental and Resource Economics 1998;14(3):431-439.

[48] Connolly D, Leahy M. A Review of Energy Storage Technologies: For the integration of fluctuating renewable energy. Available at. University of Limerick, http://www.dconnolly.net/publications.html; 2009.